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RELIABILITY OF STEP-LAP BONDED JOINTS

E. B. Birchfield, et al

McDonnell Aircraft Company

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The objective of this program was an improved technology base of data and methods applicable to the efficient design of graphite-epoxy to titanium step-lap-bonded airframe joints that are optimized for reliability under military flight loading.

A random spectrum was used in repeated load tests to establish a data base for defining lifetime and residual strength characteristics. Static strength tests were also conducted which show good comparison with prediction of an

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elastic-plastic analysis procedure. The static strength, residual strength and lifetime data were assumed to be from Weibull distributions. The shape and scale parameters for each of these distributions were calculated using the best linear unbiased (BLU) estimation procedure. Using these procedures wearout models were calibrated and checked, and conclusions concerning scaling, and translation of parameters were drawn.

Tests were also conducted to determine the effect upon lifetime of load truncation, load frequency, relaxation time between missions, and temperature.

FOREWORD

This report was prepared by McDonnell Aircraft Company, St. Louis, Missouri, 63166 under USAF Contract Number F33615-74-C-3015, Project Number 4364, and Task Number 13680126. The objective of the program was to improve the technology base of data and methods applicable to the rational and efficient design of graphite-epoxy-to-titanium step-lap bonded airframe joints that are optimized for reliability under military flight loading. The program was administered under the direction of the Air Force Flight Dynamics Laboratory by Mr. R. T. Achard, Project Engineer (AFFDL/FBS).

The program was conducted by the Structural Research Department at MCAIR, and was managed by A. J. Breining, with E. B. Birchfield as principal investigator. Major contributors to the program were Mr. L. F. Impellizzeri, Dr. R. T. Cole, and Dr. J. Hart-Smith (Douglas Aircraft Company).

This report covers the entire program contract period from January 1974 to April 1975. This report was released by the authors in April 1975.

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LIST OF SYMBOLS

A	-	Area (in^2)
A_2	-	$\beta_s^{2(r-1)}/(r-1)\ \beta_f$
A(N,M,I)	-	Weight for estimating scale parameters
a	-	$[1 - (N_o/N_p)^2]$
b	-	$a/(N_o/N_p)$
C(N,M,I)	-	Weight for estimating shape parameters
E	-	Elastic modulus (psi)
E_c	-	Effective tensile modulus of adhesive (psi)
E(CP)	-	Expected cross product
E(LB)	-	Expected loss for estimate of shape parameter
F	-	Strength (lbs) or (lbs/in)
F^{ty}	-	Tensile yield stress (psi)
F_R	-	Residual strength (lbs/in)
F_S	-	Static strength (lbs) or (lbs/in)
f	-	Frequency (cycles)
G	-	Elastic shear modulus of adhesive (psi)
G(f)	-	Power Spectral Density
L	-	Length (in)
ℓ	-	Bond Length (in)
N_o	-	Total number of zero crossings per unit time with positive slope
N_p	-	Total number of peaks per unit time
N_X	-	Cumulative peak exceedance
N_z	-	Maneuver load factor
P	-	Axial load (lbs)
$P\ (x/a\sigma)$	-	Probability of exceeding $x/a\sigma$ determined from a standard Gaussian or normal probability table

LIST OF SYMBOLS (CONTD)

$R(\tau)$	-	Autocorrelation function
r	-	$\alpha_s/2\alpha_f + 1$
T	-	Temperature (°F); lifetimes
t	-	Thickness (in)
W	-	Width (in)
$X(t)$	-	Load at time, T (lbs) or (lbs/in)
α	-	Thermal coefficient of expansion ($°F^{-1}$)
α_f	-	Weibull shape parameter for fatigue life distribution
$\alpha_R(T)$	-	Weibull shape parameter for residual strength distribution at time, T
α_s	-	Weibull shape parameter for static strength distribution
β_f	-	Weibull scale parameter for fatigue life distribution (lifetimes)
β_s	-	Weibull scale parameter for static strength distribution (lbs/in)
$\beta_R(T)$	-	Weibull scale parameter for residual strength distribution at time, T (lbs/in)
γ	-	Variance of a population
γ_e	-	Elastic shear strain (in/in)
γ_p	-	Plastic shear strain (in/in)
λ	-	$\sqrt{2G/Et\eta}$ (in^{-1})
η	-	Bondline thickness (in)
σ	-	Root mean square (RMS) of X(t)
σ_p	-	Peel stress (psi)
τ_p	-	Plastic shear stress (psi)
$(\ )_o$	-	Designates outer adherend
$(\ )_i$	-	Designates inner adherend

SECTION 1
INTRODUCTION

Joining of composite structural elements to metals or other composites is one of the most troublesome aspects of advanced composite airframe design. In theory, adhesive bonding is a most efficient approach. Although adhesive bonding eliminates many of the problems associated with stress concentrations at point attachments (such as found in conventional mechanical joints), this type of joint is subject to stress concentrations near the edge of the bond. Furthermore, a variety of failure modes are possible in the bond and adherend areas of a laminated joint. The problem of adhesive joint design is compounded for fatigue-critical applications, especially for primary-load-carrying structures where heavy overdesigned composite concepts may be employed, or where the application of composites may be rejected altogether for lack of confidence in bonded joint behavior. The ultimate goal for the technology generated under this program was practical application to improvements in the structural integrity and cost effectiveness of Air Force aircraft.

1.1 Objectives

The general objective of this program was an improved technology base of data and methods applicable to the rational and efficient design of graphite-epoxy-to-titanium step-lap-bonded airframe joints that are optimized for reliability under military flight loading. Specific objectives of the program were:

- Development of a controlled, statistically significant base of empirical data on strength and fatigue life of graphite-epoxy composite to titanium step-lap bonded joints.
- Demonstration of analytical methodology for designing step-lap bonded joints.
- Development of an analytical wearout model for step-lap bonded joints (statistical distribution of static and residual strengths, and time to failure) subjected to flight-by-flight random stress history.
- Correlation of the effects of scale-up on joint design, and definition of the non-dimensional parameters affecting scale-up.
- Determination of the effects of test variables on time to failure (test load frequencies, relaxation times, load truncation, and temperature effects).

1.2 Scope

This program was built around a conceptual structural application representative of a highly loaded aircraft structural joint. The specific application is the kick splice plate from the F-15 low cost production composite wing (Figures 1 and 2). This joint introduces loads from the lower wing skin to fuselage frame attachments. The purpose of the conceptual application was to realistically define an end item towards which this study is directed, and to provide a point of departure from which load intensities, loading spectra, environment, and scale designs for specimens could be derived.

The program was conducted in two phases. Early in Phase I a specimen verification task was conducted to select the most cost effective specimen design to establish the data base and to demonstrate that the specimens would give the desired data. This task was run using the F-15 wing root bending moment semi-random spectrum. After evaluating eleven different specimen configurations, designs for 25% scale simple double lap, 70% scale step-lap, and full scale step-lap joints were selected to establish the reliability data base. Simultaneously, a random spectrum for the F-15 wing root bending moment was developed. This spectrum was subsequently used in all repeated load tests to establish the data base for defining lifetime and residual strength characteristics. The static strengths of the tested specimens were compared with the predictions of the elastic-plastic analysis. The static strength, residual strength and lifetime data were assumed to be from Weibull distributions. The shape and scale parameters for each of these distributions were calculated using the best linear unbiased (BLU) estimation procedure. Using these parameters, the wearout models were calibrated and checked, and conclusions concering scaling, and translation of parameters were drawn.

In Phase II, tests were conducted to determine the effect upon lifetime of load truncation, load frequency, relaxation time between missions, and temperature.

In this program, a total of 278 specimens in addition to those required for specimen design verification were fabricated. Of these, one hundred and eighty-eight were tested to provide the empirical data base. Ninety specimens were delivered for testing by the Air Force. Specimens evaluated in this program to establish the reliability data base are shown in Table 1.

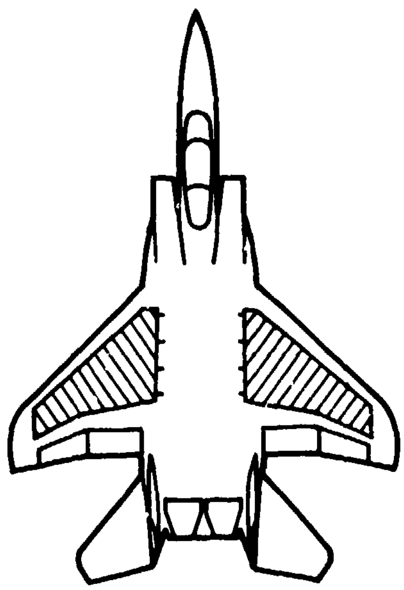

FIGURE 1 F-15 HIGH PERFORMANCE FIGHTER

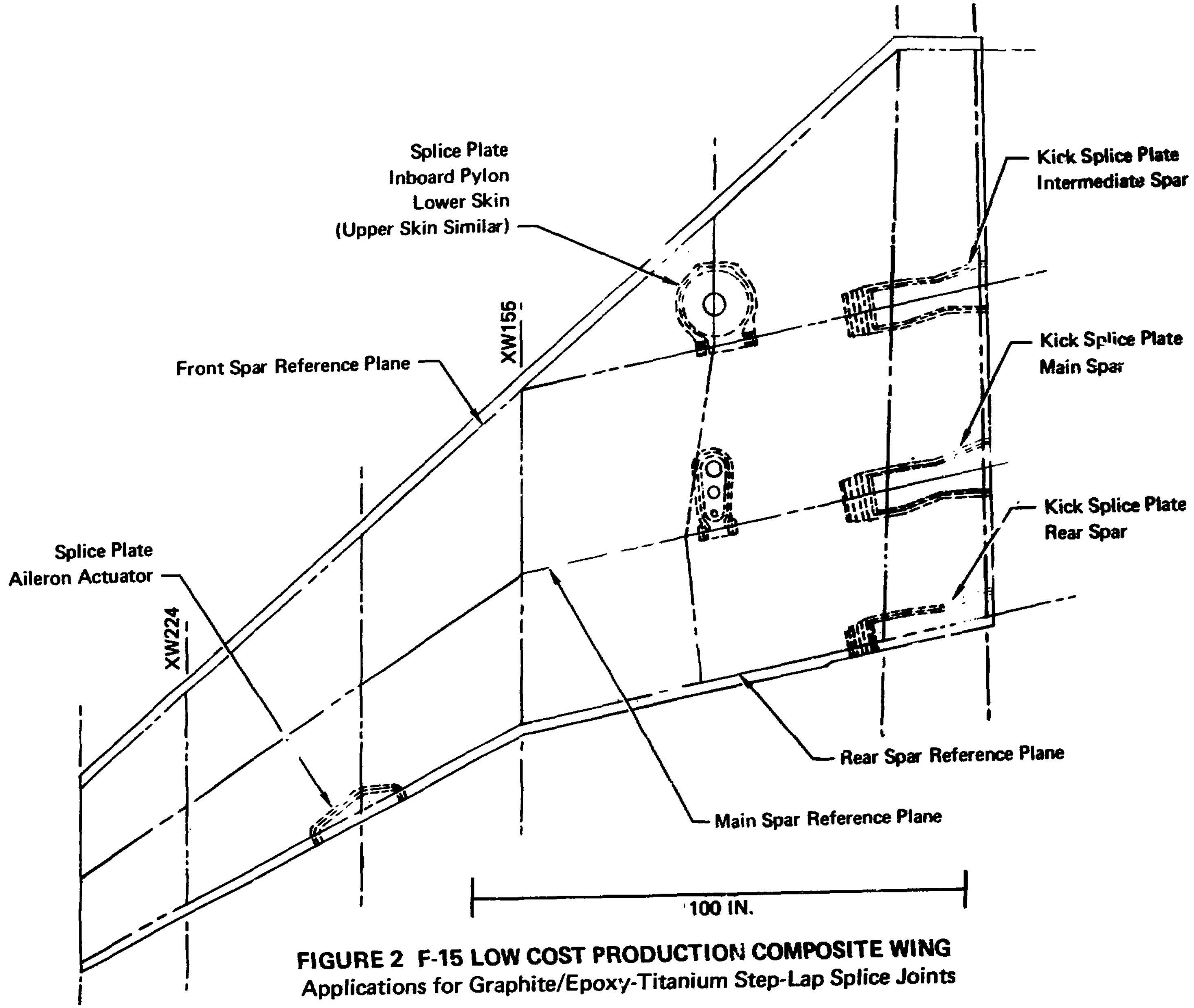

FIGURE 2 F-15 LOW COST PRODUCTION COMPOSITE WING
Applications for Graphite/Epoxy-Titanium Step-Lap Splice Joints

TABLE 1 SPECIMEN PLAN FOR THE RELIABILITY DATA BASE

	Description of Testing	No. of Simple Joints	No. of Small Step-Lap Joints	No. of Full Scale Step-Lap Joints	Random Spectrum Identification No.
PHASE I	Static	8	10	10	
	Residual (2 Life Times)	–	10	10	1
	Residual (3 Life Times)	10	10	10	1
	Fatigue (Run-Out) or 6 Life Times	10	40	30	1
	USAF Testing	60	30		
	Total Phase I Specimens	88	100	60	
	Total Phase I Tests	28	70	60	
PHASE II	Frequency Effects	–	–	6	3
	Relaxation	–	–	6	4
	Truncation	–	–	6	2
	Temperature	–	–	12	1
	Total Phase II	–	–	30	
TOTAL PROGRAM	Specimens	88	100	90	
	Tests	28	70	90	

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SECTION 2

SPECIMEN SELECTION, DESIGN AND ANALYSIS

Three specimen types were selected for testing in this program in order to provide an improved technology data base and methodology applicable to the efficient design of graphite-epoxy-to-titanium step-lap bonded joints. The kick splice plate for the F-15 low cost production composite wing (Figure 3) was selected as the basic conceptual structural application around which the program was built. One of the principal reasons for this selection was that the joint is representative of a USAF high performance aircraft primary load carrying joint and its basic design characteristics and requirements are well-defined. Specimen designs selected for testing in this program are: (1) simple double lap joints, (2) small scale step-lap joints, and (3) full scale step-lap joints. The requirements placed on the specimens are derived from the conceptual structural application and are discussed in paragraph 2.1. The methodology used in the design and analysis of these specimens is detailed in paragraph 2.2. At the start of the program a specimen verification task was conducted to verify that the specimens would yield representative data. The specimen verification task and the selection of the specimen design to establish the data base for the remainder of the program are discussed in paragraph 2.3 and the analysis of these specimens is presented in paragraph 2.4.

2.1 Requirements

The requirements placed on the specimens are derived from the F-15 low cost production wing kick splice, the conceptual structural application. This structural application is an internal MCAIR conceptual study. An additional objective was to achieve bondline failures rather than laminate failures. The layup of the graphite-epoxy in the splice through a section along the spar is a balanced laminate (36.4% $\pm$45°, 54.5% 0°, 9.1% 90°). The ultimate static strength of the splice must be greater than or equal to 15,000 lb/in. Design limit load (DLL) for the splice in 10,000 lb/in. The endurance must be greater than or equal to 4 lifetimes (16,000 flight hours). With the above considerations in mind, the specimens were designed to meet the following objectives:

Simple Double-Lap Joints

- Must fail in bondline
- Must be stiffness balanced with adherends scaled from full scale step-laps

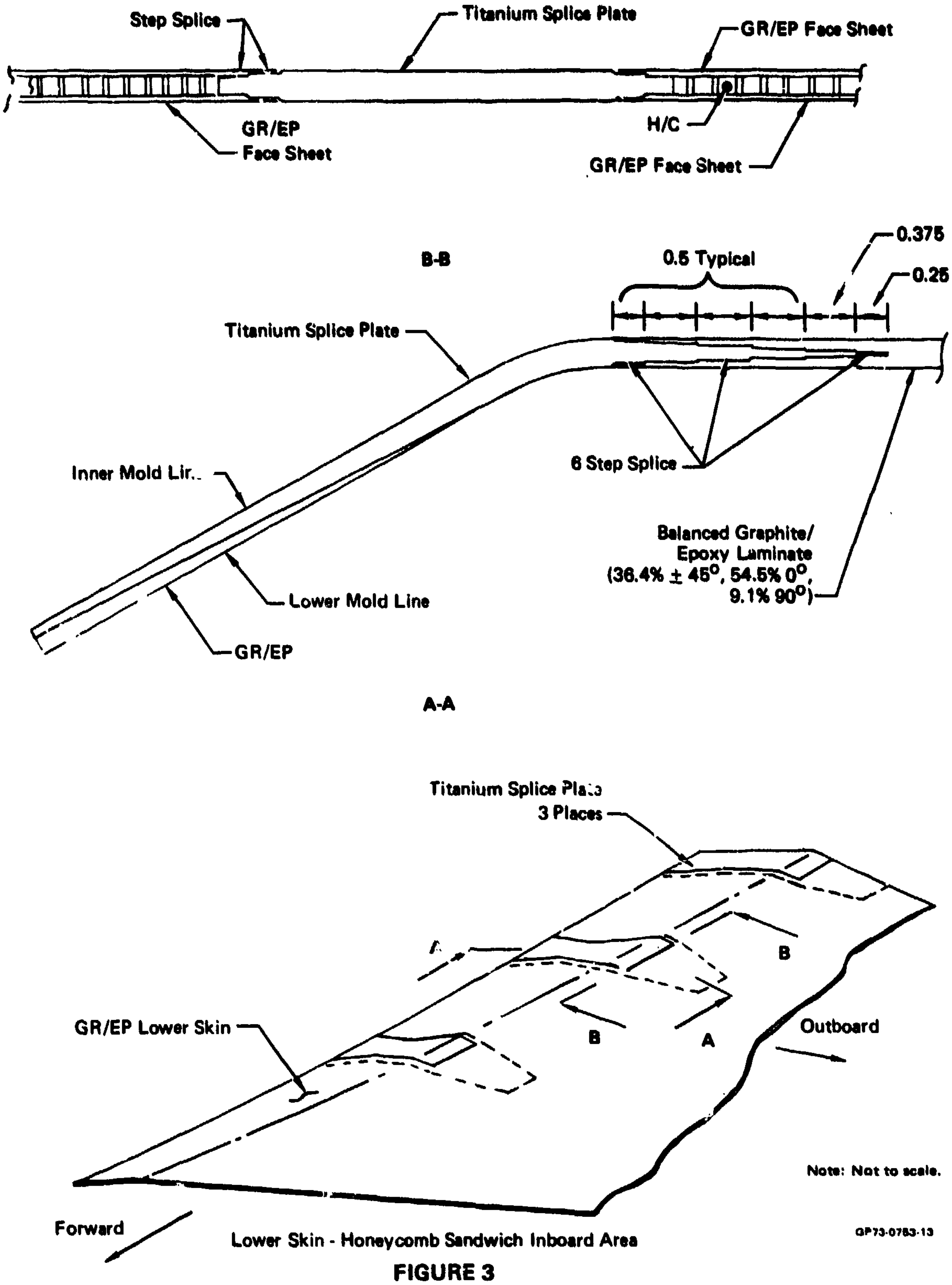


FIGURE 3

F-15 LOW COST PRODUCTION COMPOSITE WING CONCEPTUAL JOINT APPLICATION

- o Must have full scale bondline

Small Scale Step-Lap Joints

- o Must have the same number of steps as the full scale step-lap joints
- o Must have the same laminate layup percentagewise on each step as the full scale step-lap joints (limited by need to have integral numbers of plies).
- o Must have scaled thickness on each step (limited by need to have integral numbers of plies).
- o Must have scaled lap length.
- o Must have scaled adhesive system.

Full Scale Step-Lap Joints

- o Must have same layup (36.4% ±45°, 54.5% 0°, 9.1% 90°) as F-15 lower skin at splice
- o Must fail in bondline
- o Must have a static strength greater than or equal to 15,000 lbs/in
- o Must have an endurance greater than or equal to 4 lifetimes under the F-15 wing root bending moment random spectrum (developed in this program) with DLL greater than or equal to 10,000 lbs/in.

2.2 Analytical Methods

Two analytical methods guided design of the test specimens. The analysis approach for static strength design is described in paragraph 2.2.1 below. The analyses to assure that joint designs meet lifetime requirements is described in paragraph 2.2.2.

2.2.1 Static Strength Design - The procedure used to design joints for static strength is based on the elastic-plastic analysis of Reference 1-6. This procedure, as it applies first to double lap joints and then to step-lap joints, is described in the paragraphs which follow. The impact of this analysis on scaling adhesive bonded joints is discussed.

2.2.1.1 Double Lap Joint - A typical double lap joint is illustrated in Figure 4. To analyze this joint, it is first stiffness balanced with $E_i t_i$ held constant (see Figure 5). The strength of the balanced joint is then determined from Figure 6, where λ is given by equation (1)

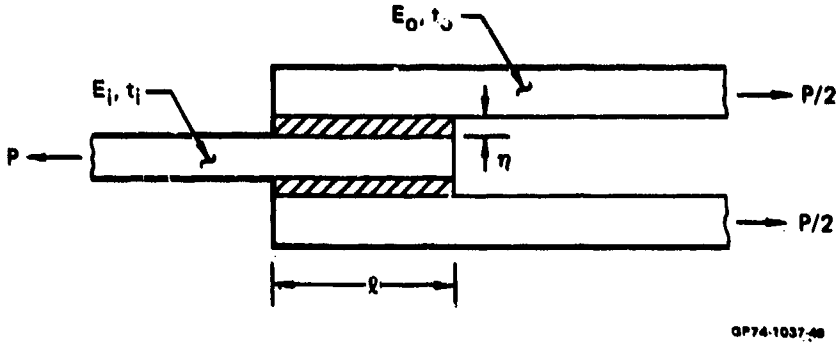


FIGURE 4 TYPICAL DOUBLE LAP JOINT

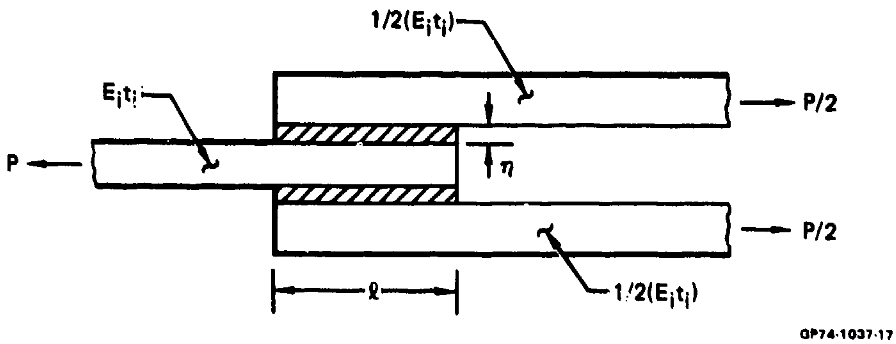


FIGURE 5 STIFFNESS BALANCED (E_it_i CONSTANT) DOUBLE LAP JOINT

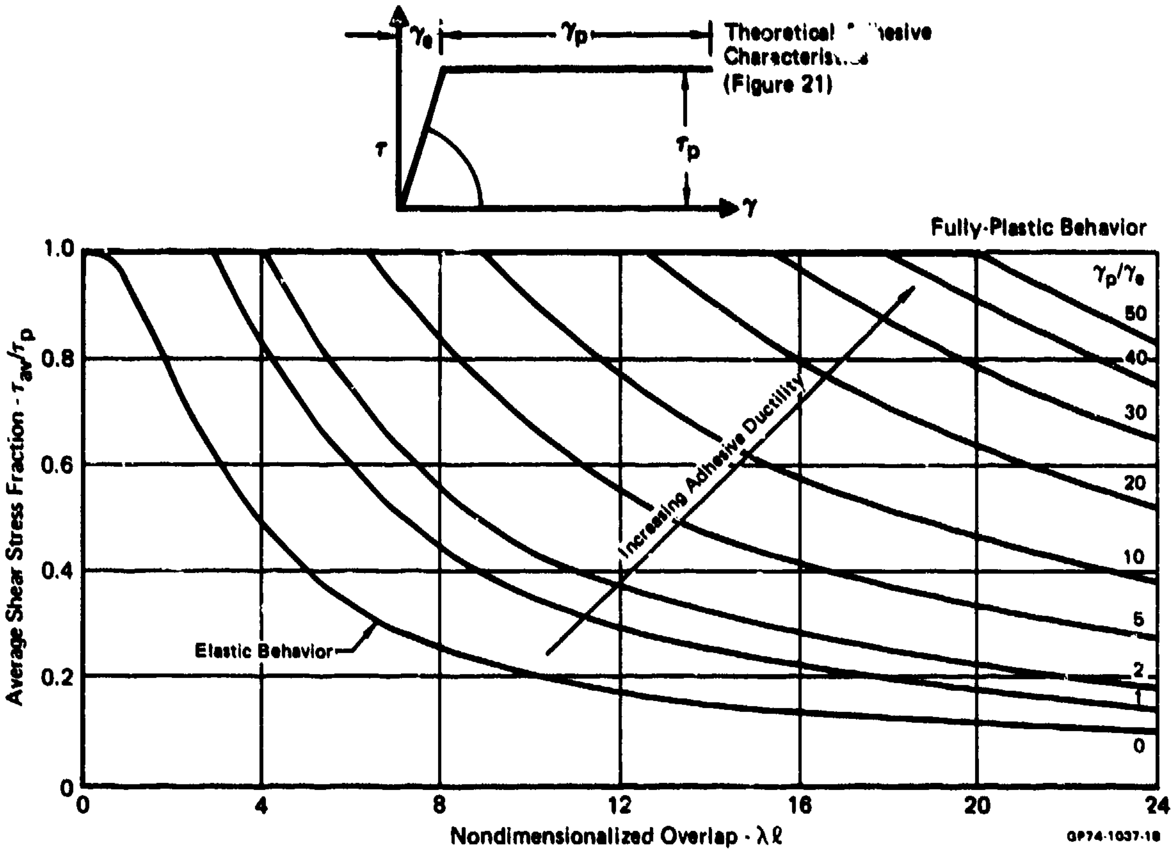


FIGURE 6 AVERAGE SHEAR STRESSES IN DOUBLE-LAP ADHESIVE BONDS

$$\lambda = \sqrt{2G/Et\eta} \tag{1}$$

where G is the adhesive shear modulus and η is the bondline thickness. Figure 7 is used to correct for the stiffness imbalance. Figure 8 is used to correct for thermal imbalance. The maximum peel stress in the adhesive is given by equation (2).

$$\sigma p = \tau p \left[\frac{3E_c'(1 - \mu^2)t_o}{E_o\eta}\right]^{1/4} \tag{2}$$

where E_c' is the "effective" tensile modulus of the adhesive

$$\frac{1}{E_c'} = \frac{1}{E_c} + \frac{k_1}{E_{in}} + \frac{k_2}{E_{on}}$$

E_{in} and E_{on} are the transverse tensile moduli of the inner and outer adherends respectively. The constants k_1 and k_2 refer to the number (or fraction) of adhesive layer thicknesses for which the adherends are affected by the peel stresses. These equations are derived in Reference 2.

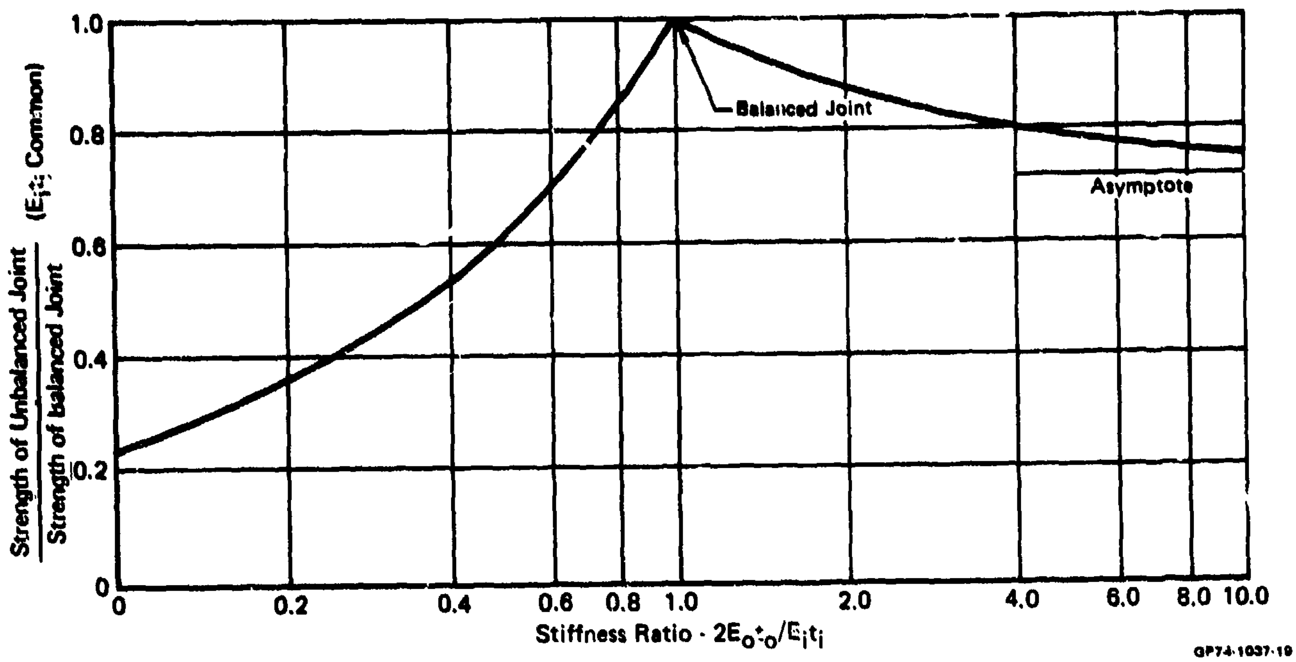


FIGURE 7 STRENGTH REDUCTION IN BONDED JOINTS DUE TO ADHEREND STIFFNESS IMBALANCE

2.2.1.2 Step-Lap Joints - The procedure used to design step-lap joints is outlined below:

- o Adherends - the adherend thickness and the laminate layup are determined from strength requirements
- o Number of Steps - initially determined by dividing the total number of plies by 8 and rounding off to next highest whole number
- o Stacking Sequence - a zero degree ply is placed on the face of each step; the plies are interspersed to avoid adverse stacking effects
- o Length of Bondline - assume that the joint is scarfed; the length of a scarfed joint required to carry a load P is given by equation (3)

$$\ell = P/\tau_p \; [E_2t_2/E_1t_1] \qquad (3)$$

where

$$E_2t_2 > E_1t_1$$

- o Length of Each Step - select the length of the tang (the thinnest titanium step) so that is would not yield if the adhesive on it was totally plastic, thus its length is given by equation (4)

$$\ell = tF^{ty}/2\tau p \qquad (4)$$

(machining tolerances require that the thickness of the tang exeeed 0.021 inch).

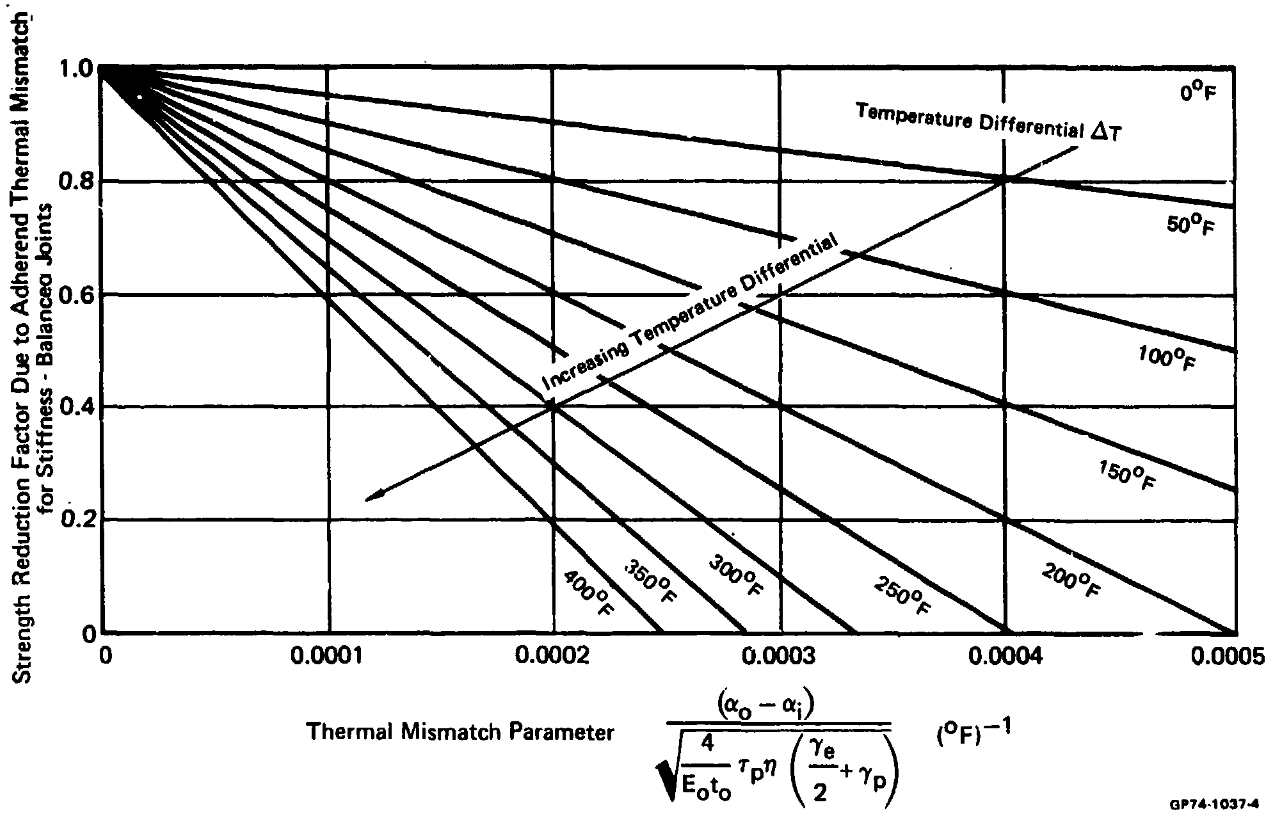


FIGURE 8 STRENGTH REDUCTION FACTOR IN DOUBLE-LAP BONDED JOINTS, DUE TO ADHEREND THERMAL MISMATCH

- o Optimization - iterative changes to joint dimensions to maximize joint strength) - (computer program A4EGX described in Appendix A may be used to perform required computations).

2.2.1.3 Scaling Joints - To scale a structural element it is first necessary to recognize the nondimensional parameters which control the stresses in the element. If these parameters are held constant while the characteristic physical dimensions are scaled the failure load will also be scaled. In Reference 14 the nondimensional parameters which control the bondline shear and normal stresses and the adherend axial stresses are shown to be:

$$E_o t_o / E_i t_i, \qquad \gamma_p / \gamma_e, \qquad \text{and} \qquad \ell \sqrt{G/\eta E_o t_o}$$

and

$$\Delta\alpha\Delta T \; E_o t_o / \tau_p \eta, \qquad E_c' \; (1-\nu^2) t_o / E_o \eta$$

(on each step).

Upon examination of these parameters it can be seen that the proper scaling parameters for step-lap joints are ℓ, t_i, t_o and η. The same materials and the same percentage layups must also be used. In practice, such scaling cannot be exact because: (a) tolerances make it difficult to produce actually scaled bond lengths; (b) materials usually have a fixed per-ply thickness; (c) actual values of bondline thickness are hard to determine and control because of adhesive migration into the composite resin. Bondline thickness is probably a direct function of the adhesive carrier thickness which is normally made with minimum thickness material. An additional uncertainty is associated with the requirement that all adhesive properties remain constant when the bondline thickness is varied.

2.2.2 Lifetime Analysis - The Air Force anticipates incorporating into the Advanced Structural Integrity Program a definite approach for verifying the damage tolerance of safety of flight structure fabricated from advanced composite materials. An analytical as well as an experimental qualification for lifetime will be required. Previous analysis methods for metal structures included the use of Miner's rule in conjunction with a massive amount of data, including smooth S-N curves over a range of stress ratios, stable cyclic stress strain curves, and a notch analysis.

Aircraft which are now in the conceptual stage are showing a considerable usage of advanced composite materials and adhesive bonded jointing. The problem of providing the analytical qualification for these aircraft will be complicated primarily because the required data base is not available and because the cost of generating such a base would be astronomical especially considering the tailorability of composite materials.

To provide an adequate data base at minimum cost, a wearout model (probability statement for residual strength as a function of lifetimes under a fixed spectrum and load level) presented in equation (5), derived in Reference 8, and summarized in Appendix B was used:

$$P[F(t) > F] = \exp - \left[\frac{F^{2(r-1)} + A_4(r-1)t}{\beta_s^{\,2\,(r-1)}}\right]^{\alpha_f} \tag{5}$$

where

α_s = static shape parameter

β_s = static scale parameter

α_f = fatigue shape parameter

β_f = fatigue scale parameter

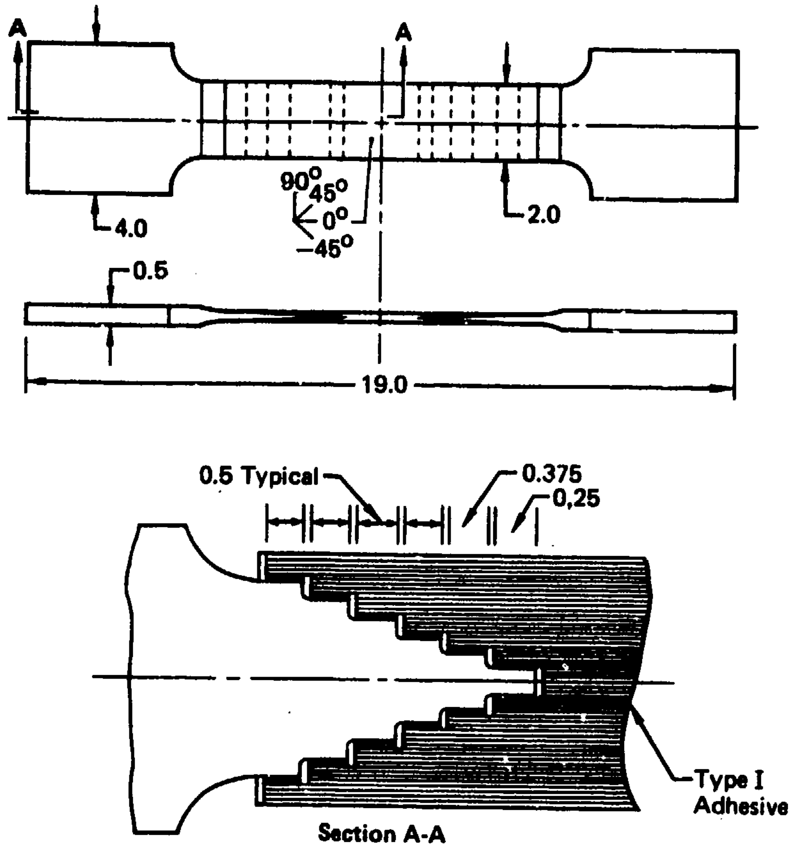
α_f = $\alpha_s/2(r-1)$

β_f = $\beta_s^{\,2(r-1)}/A_4(r-1)$

To calibrate this model, it was necessary to perform static strength and lifetime tests under a spectrum loading, to assume a Weibull distribution for these variables, and to estimate the parameters of the distributions for the element of interest.

2.3 Verification and Selection of Specimen Design for Reliability Data Base

At the start of the program a specimen verification task was conducted to assure specimens would yield representative data. In this task, eleven different specimens (Figure 9 thru Figure 20) were designed. All but the specimens of Figures 12 and 20 were fabricated, and tested. The test results are listed in Tables 2 and 3. For the lifetime tests for the verification task the F-15 wing root bending moment semi-random spectrum was used, since it was the most representative spectrum available at the time. A random spectrum was developed and used for the remaining tasks. Based on



Ply No.	Oreinta-tion	Ply No.	Orienta-tion
1	45°	26	45°
2	0°	27	−45°
3	−45°	28	45°
4	0°	29	0°
5	45°	30	−45°
6	0°	31	0°
7	−45°	32	0°
8	0°	33	45°
9	90°	34	0°
10	0°	35	0°
11	45°	36	−45°
12	0°	37	0°
13	90°	38	90°
14	0°	39	0°
15	−45°	40	45°
16	0°	41	0°
17	0°	42	90°
18	45°	43	0°
19	0°	44	−45°
20	0°	45	0°
21	−45°	46	45°
22	0°	47	0°
23	45°	48	−45°
24	−45°	49	0°
25	45°	50	45°

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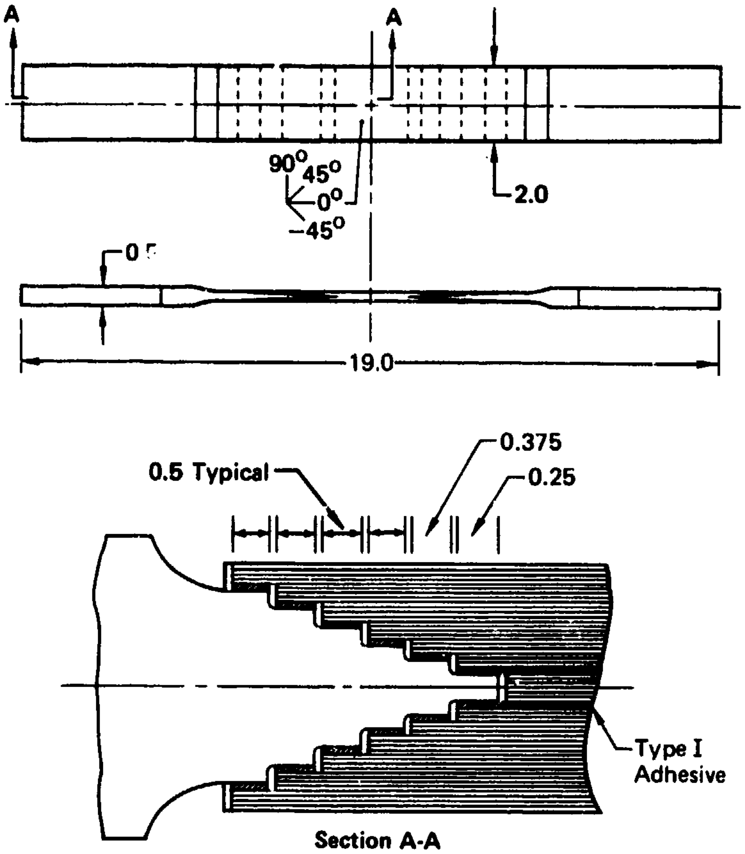
FIGURE 9 FULL SCALE, STEP-LAP SPECIMEN TWO INCHES WIDE, DOG BONED GRIPS



Ply No.	Orientation	Ply No.	Orientation
1	45°	26	45°
2	0°	27	−45°
3	−45°	28	45°
4	0°	29	0°
5	45°	30	−45°
6	0°	31	0°
7	−45°	32	0°
8	0°	33	45°
9	90°	34	0°
10	0°	35	0°
11	45°	36	−45°
12	0°	37	0°
13	90°	38	90°
14	0°	39	0°
15	−45°	40	45°
16	0°	41	0°
17	0°	42	90°
18	45°	43	0°
19	0°	44	−45°
20	0°	45	0°
21	−45°	46	45°
22	0°	47	0°
23	45°	48	−45°
24	−45°	49	0°
25	45°	50	45°

FIGURE 10 FULL SCALE, STEP LAP SPECIMEN TWO INCHES WIDE, CONSTANT WIDTH

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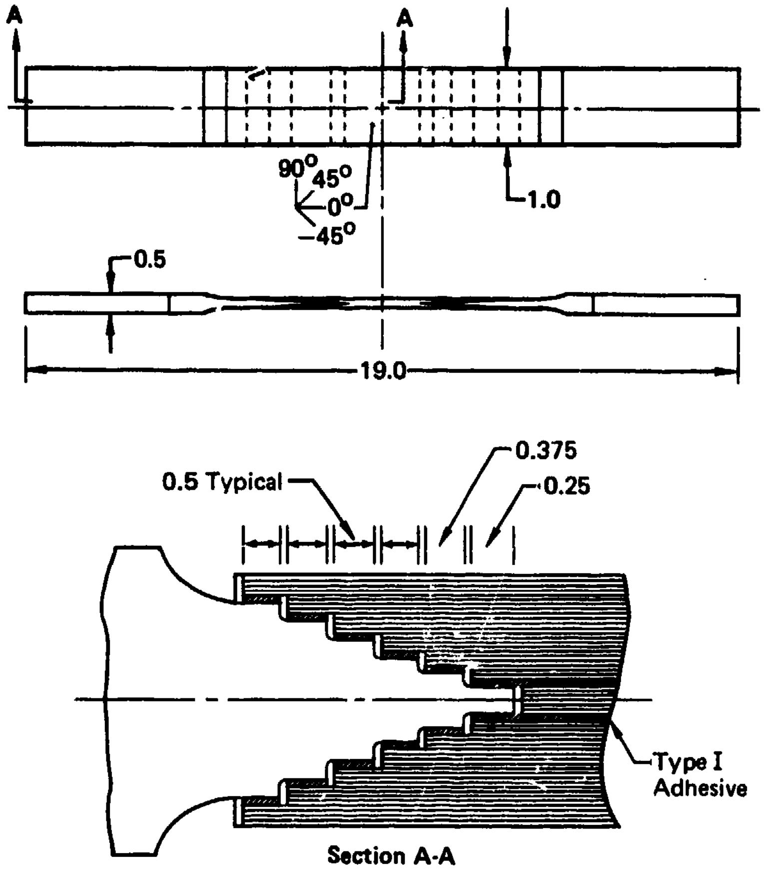

Ply No.	Orienta-tion	Ply No.	Orienta-tion
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3	−45°	28	45°
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7	−45°	32	0°
8	0°	33	45°
9	90°	34	0°
10	0°	35	0°
11	45°	36	−45°
12	0°	37	0°
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19	0°	44	−45°
20	0°	45	0°
21	−45°	46	45°
22	0°	47	0°
23	45°	48	−45°
24	−45°	49	0°
25	45°	50	45°

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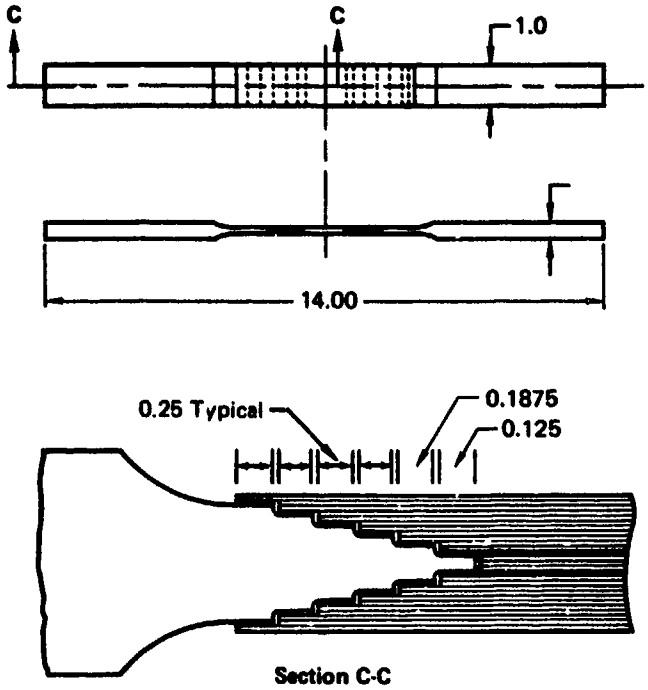
FIGURE 11 FULL SCALE STEP-LAP SPECIMEN CONSTANT WIDTH



Ply No.	Orienta-tion	Ply No.	Orienta-tion
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2	45°	15	0°
3	0°	16	−45°
4	−45°	17	0°
5	0°	18	45°
6	90°	19	0°
7	0°	20	90°
8	45°	21	0°
9	0°	22	−45°
10	−45°	23	0°
11	0°	24	45°
12	45°	25	0°
13	90°		

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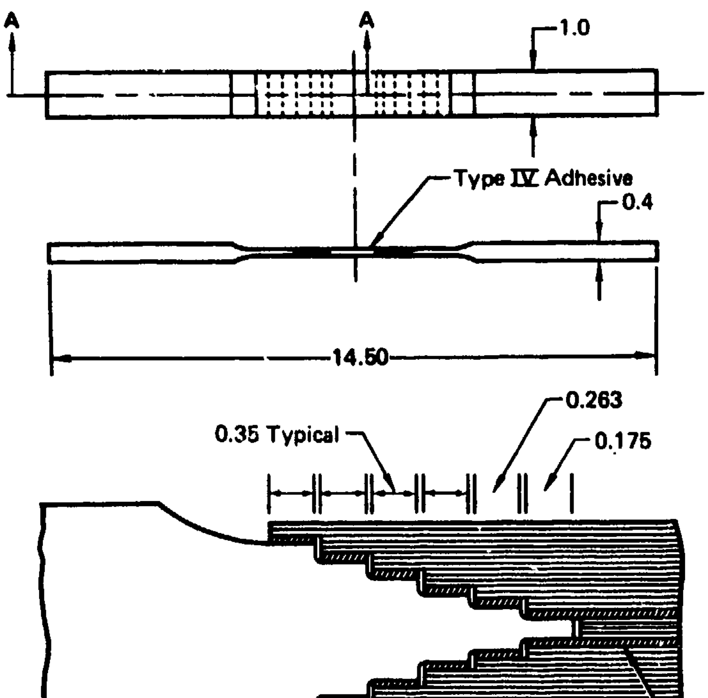
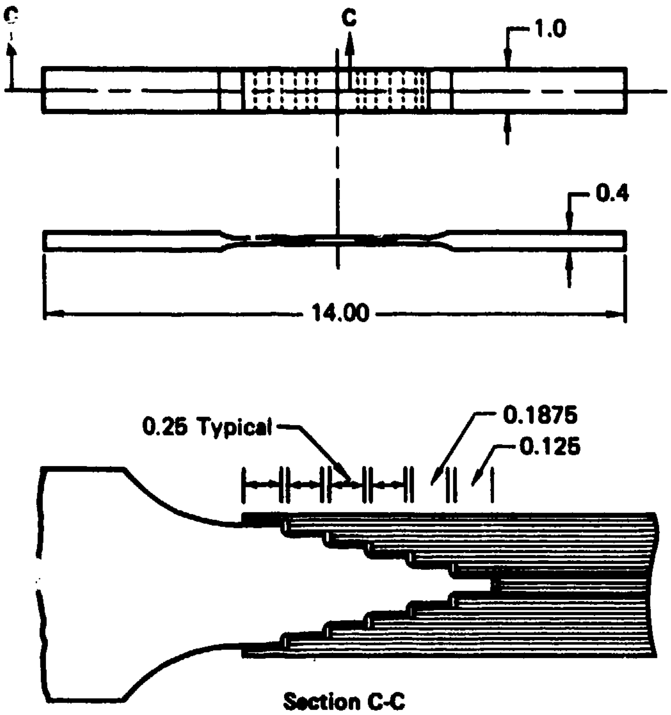
FIGURE 12 50% SCALE, STEP-LAP SPECIMEN, 50% SCALE ADHESIVE



Ply No.	Orienta-tion	Ply No.	Oreinta-tion
1	45°	18	−45°
2	0°	19	45°
3	−45°	20	0°
4	0°	21	−45°
5	0°	22	0°
6	45°	23	45°
7	90°	24	0°
8	0°	25	0°
9	−45°	26	−45°
10	0°	27	0°
11	0°	28	90°
12	45°	29	45°
13	0°	30	0°
14	−45°	31	0°
15	0°	32	−45°
16	45°	33	0°
17	−45°	34	45°

GP74-1037-9

FIGURE 13 70% SCALE STEP-LAP SPECIMEN, 70% ADHESIVE



Ply No.	Orienta-tion	Ply No.	Orienta-tion
1	0°	14	−45°
2	45°	15	0°
3	0°	16	−45°
4	−45°	17	0°
5	0°	18	45°
6	90°	19	0°
7	0°	20	90°
8	45°	21	0°
9	0°	22	−45°
10	−45°	23	0°
11	0°	24	45°
12	45°	25	0°
13	90°		

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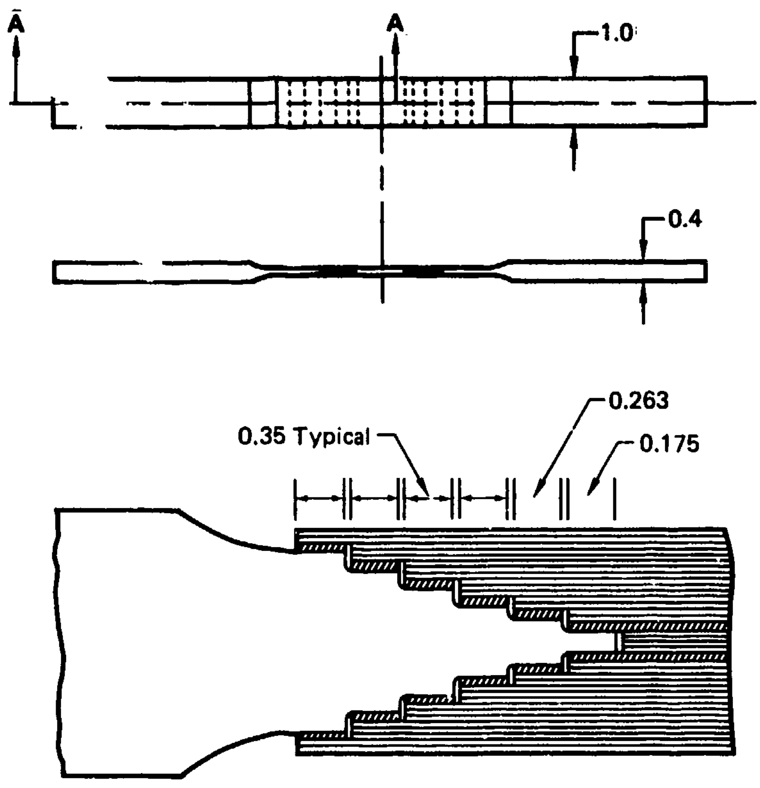
FIGURE 14 50% SCALE, STEP-LAP SPECIMEN, FULL SCALE ADHESIVE



Ply No.	Orienta-tion	Ply No.	Oreinta-tion
1	45°	18	−45°
2	0°	19	45°
3	−45°	20	0°
4	0°	21	−45°
5	0°	22	0°
6	45°	23	45°
7	90°	24	0°
8	0°	25	0°
9	−45°	26	−45°
10	0°	27	0°
11	0°	28	90°
12	45°	29	45°
13	0°	30	0°
14	−45°	31	0°
15	0°	32	−45°
16	45°	33	0°
17	−45°	34	45°

Section A-A

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FIGURE 15 70% SCALE, STEP-LAP SPECIMEN, FULL SCALE ADHESIVE

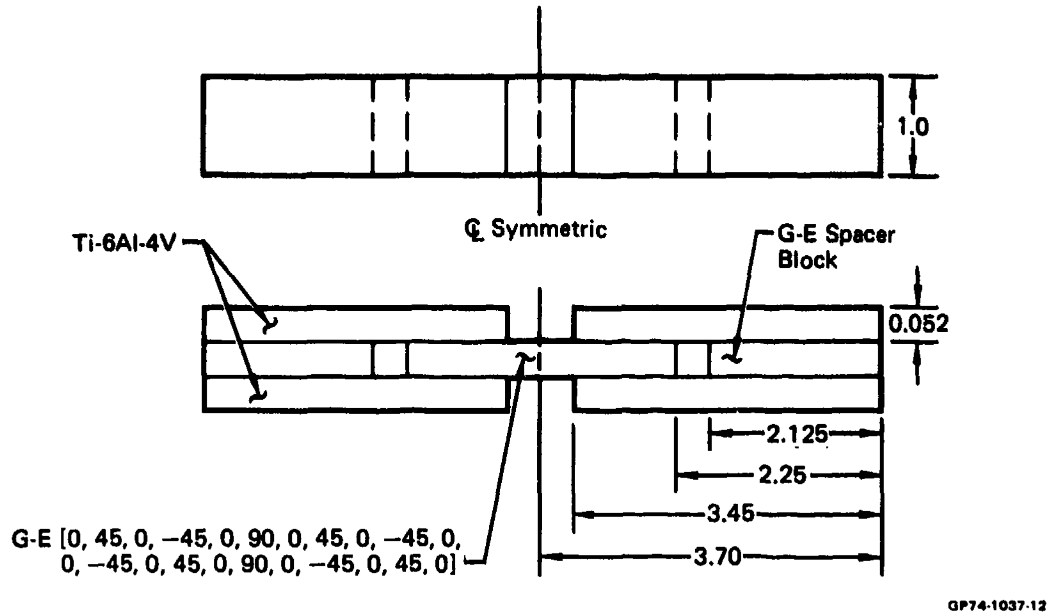

FIGURE 16 50% SCALE, DOUBLE LAP SPECIMEN, FULL SCALE ADHESIVE

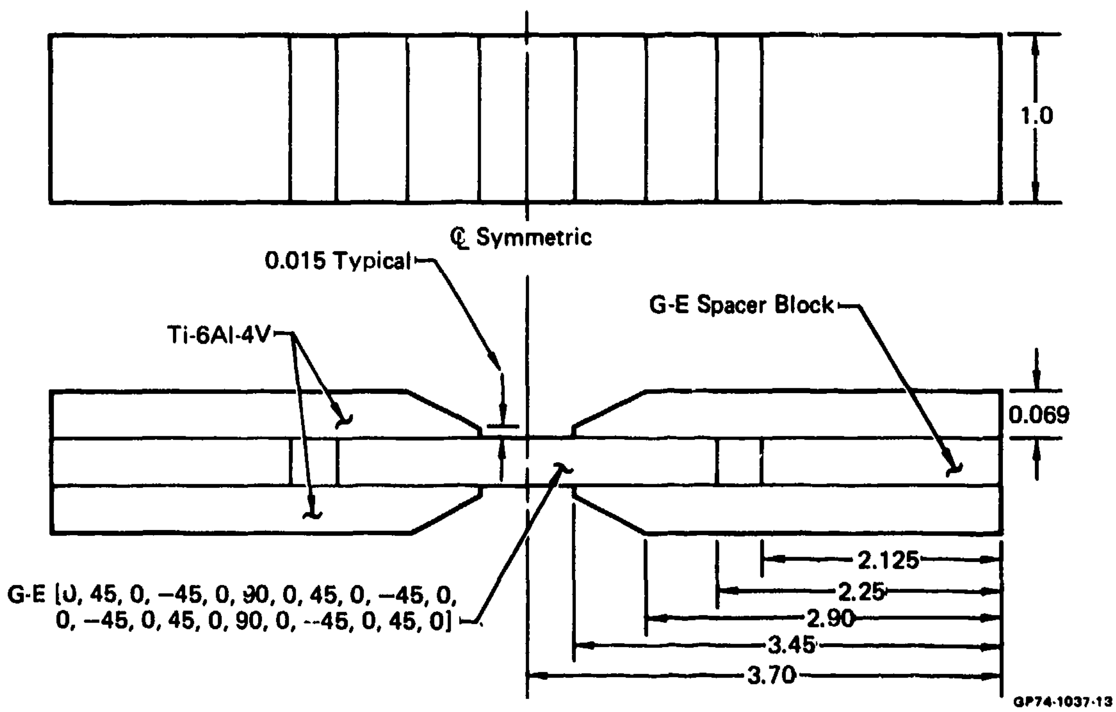

FIGURE 17 50% SCALE, TAPERED LAP SPECIMEN, FULL SCALE ADHESIVE

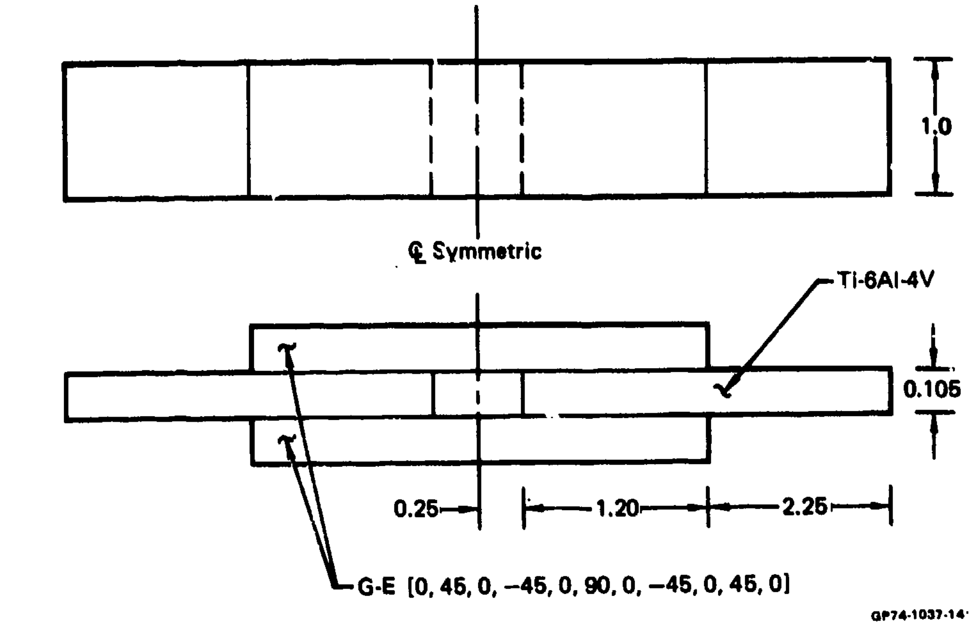

FIGURE 18 50% SCALE, DOUBLE LAP SPECIMEN, FULL SCALE ADHESIVE

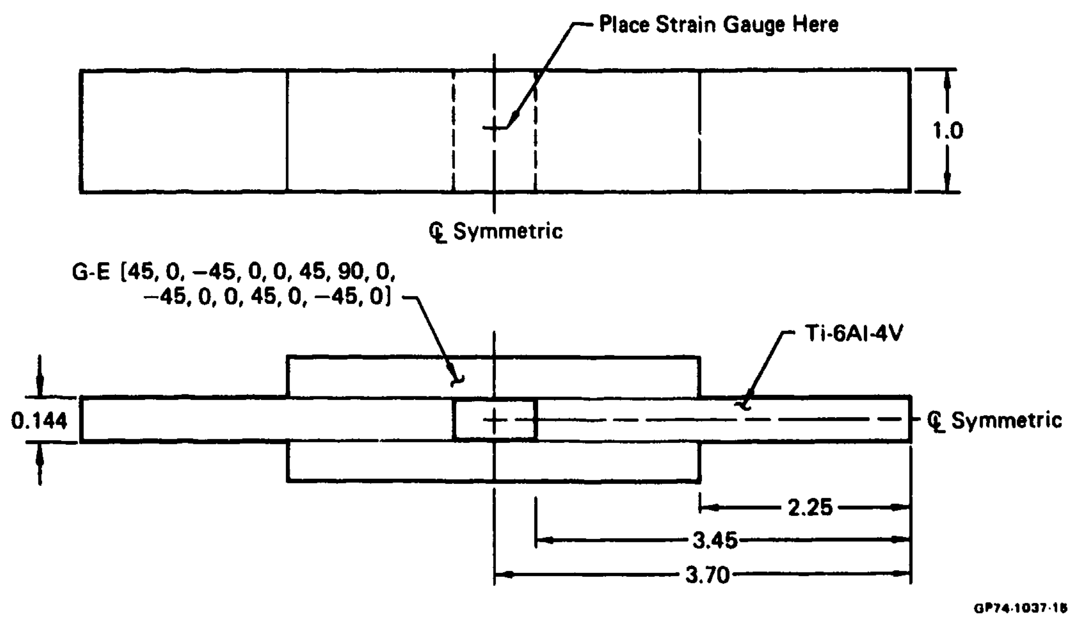

FIGURE 19 70% SCALE, DOUBLE LAP SPECIMEN 70% SCALE ADHESIVE

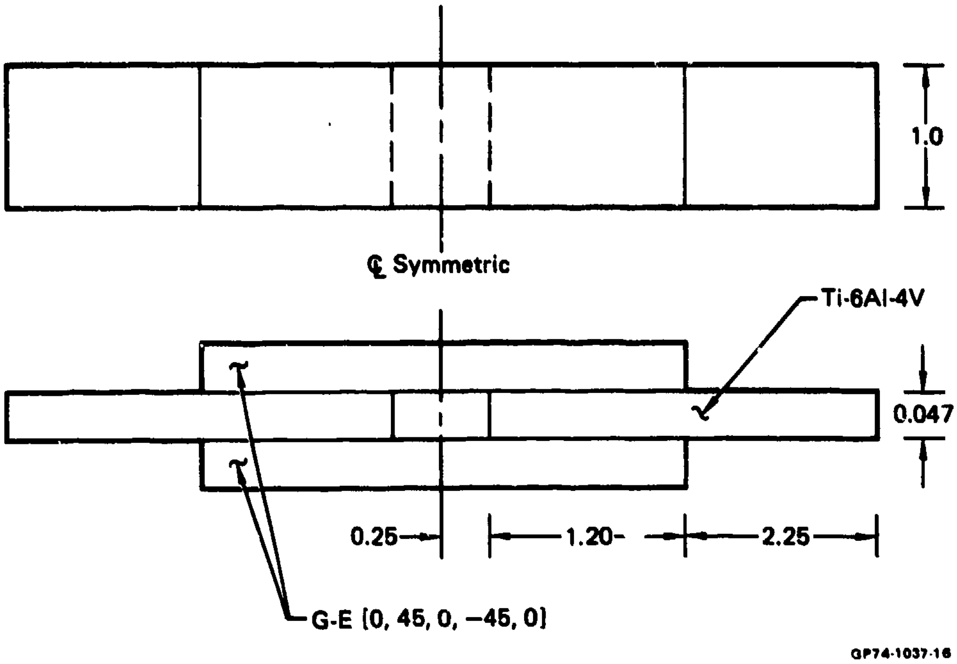

FIGURE 20 SIMPLE SPECIMEN (25% SCALE DOUBLE LAP) FULL SCALE ADHESIVE

TABLE 2 STATIC STRENGTH TESTS CONDUCTED UNDER VERIFICATION TASK

Specimen Description (Figure)	Reference No.	Predicted Strength (lb/in.)	Failure Load (lb)	Width (in.)	Running Load at Failure (lb/in.)
9	1	17,629	37,750	2.012	18,760
	2	17,629	31,500	1.965	16,030
10	1	17,629	34,300	1.954	17,550
11	1	17,629	19,125	0.995	19,220
	2	17,629	20,850	1.002	20,810
	3	17,629	18,750	0.994	18,860
13	1	12,341	14,750	0.988	14,930
	2	12,341	15,300	0.993	15,410
	3	12,341	14,825	0.975	15,210
14	1	9,376	11,400	0.994	11,470
	2	9,376	11,328	0.987	11,480
	3	9,376	11,000	0.996	11,040
15	1	13,340	15,800	1.001	15,780
	2	13,340	16,200	0.998	13,230
	3	13,340	13,400	1.001	13,390
16	1	8,600	4,050	1.057	3,830
	2	8,600	4,175	1.040	4,010
	3	8,600	3,690	1.061	3,480
17	1	4780	3,880	1.044	3,720
	2	4780	3,735	1.051	3,550
	3	4780	3,415	1.061	3,220
18	1	8,600	9,550	1.010	9,460
	2	8,600	10,750	1.001	10,740
	3	8,600	11,475	1.003	11,440
19	1	8,200	11,450	1.004	11,400
	2	8,200	10,850	1.004	10,810
	3	8,200	10,700	1.003	10,670

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TABLE 3 FATIGUE LIFE TESTS CONDUCTED UNDER VERIFICATION TASK

Specimen Description (Figure)	Reference No.	Test Limit Load (lb)	Width (in.)	Life Times	Last Load (%TLL[2])	Residual Strength (lb)
9	1	22,900	2.001	4.0000		25,[illegible]75
	2	24,000	1.998	2.0000	125	
10	1	19,600	1.999	4.0000		37,000
	2	22,900	2.001	4.0000		28,500
11	1	13,050	0.993	4.0000		14,850
	2	13,700	0.998	2.4200	87	
	3	13,700	1.001	3.3000	81	
	4	13,700	0.999	2.0000	125	
13	1	9,280	0.987	3.5000	109	
	2	9,280	0.978	3.5000	101	
	3	9,280	0.988	3.0300	91	
14	1	5,295	1.005	4.0000		11,925
	2	7,150	1.003	2.1900	80	
	3	7,150	1.003	1.1700	74	
15	1	9,500	1.001	3.3050		
	2	9,300	1.000	2.0000	113	
	3	9,000	0.998	3.1790	75	
16	1	1,994	0.993	4.0000		(1)
	2	2,650	1.003	4.0000		(1)
	3	3,000	1.001	0.0325	87	
17	1	1,840	1.001	4.0000		(1)
	2	2,452	1.005	4.0000		(1)
	3	2,900	1.003	4.0000		(1)
18	1	5,295	1.005	4.0000		(1)
	2	7,150	1.003	2.1900	82	
	3	7,150	1.003	1.1700	74	
19	1	5,500	1.005	4.0000		10,675
	2	7,150	1.004	2.9200	89	
	3	7,150	1.001	4.0000		11,600

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(1) No residual tests were run since the data would not help in specimen selection
(2) Test limit load (TLL)

the results of these tests, three specimen types (Figures 11, 13 and 20) were selected for testing to establish the program data base. Simultaneously the random spectrum for the F-15 wing root bending moment was developed for use in lifetime and residual strength tests. The three specimen configurations selected to establish the reliability data base are discussed in the following paragraphs.

2.3.1 Full Scale Step-Lap Specimen Development - Several specimen configurations were evaluated during the specimen verification task. One of the first configurations evaluated is shown in Figure 9. The grips of this specimen were thicker and wider than the test area to avoid possible grip failures caused by the unknown stress concentration factor associated with the serrated grips on the fatigue test machine. Also early in the program several specimens were fabricated without the additional grip width, Figure 10. These specimens were tested and no grip failures occurred (Tables 2 and 3). These specimens (Figures 9 and 10) were two inches wide to minimize edge effects. One inch wide specimens were tested statically and compared with the results of the two inch wide specimens. The comparison is presented in Table 2. From this table it can be seen that the average running load is nearly the same for each specimen. This implies that the edge effects for the one inch wide specimen are minimal. Thus, the one inch wide full scale step-lap specimen (Figure 11) was selected to establish the data base.

2.3.2 Small Scale Step-Lap Specimen Development - Originally, the small scale step-lap specimen was selected to be 50% of full scale (Figure 12). This scale was judged to be the minimum practical in which to simulate realistic ply distributions. At this time, it was assumed that the bondline thickness (and thus adhesive scale) could be controlled with the bonding pressure. Upon further investigation, it was found that the adhesive thickness was controlled by the thickness of the adhesive carrier (FM-400 is an epoxy adhesive with an aluminum filler and a nylon carrier). Only two FM-400 adhesive systems were available; these were type I and type IV. The physical characteristics of these systems (as provided by American Cyanimid, the adhesive manufacturer) are presented in Table 4. Type IV adhesive is 70% as thick as Type I adhesive. Consequently, the small scale joints were designed to be 70% of full scale in order to use scaled adhesives. The 70% scale step-lap specimen (Figure 13) was selected to establish the required data base.

TABLE 4 PHYSICAL CHARACTERISTICS OF FM-400 SYSTEMS

Scale	Type	Weight (lb/ft^2)	Nylon Carrier Specification	Carrier Thickness (in.)	Nominal Bondline Thickness (in.)
1.0	I	0.10	EP-15	0.0063	0.007
0.7	IV	0.07	TC-15	0.0045	0.005

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2.3.3 Simple Specimen Development - The simple specimen configuration was originally selected to represent 50% scale design (Figures 16 and 17) for investigation of scale and complexity effects by comparison with the 50% step-lap joints. At the same time the transferrability of the Weibull parameters could be investigated which is the primary function of these specimens. It had been postulated (Reference 11) that the Weibull static shape parameter would be the same for simple specimens and full scale specimens as long as the failure modes (cohesion) are the same. The tapered double-lap specimens were selected to account for the possibility that the double lap specimens might fail in peel. Graphite-epoxy was used as the central adherend for tapered lap specimens because the specimens could not be fabricated otherwise. Graphite-epoxy was used as the central adherend in the double-lap specimen for consistency with the tapered lap specimens. Several specimens were fabricated to these configurations and tested. The results are also presented in Tables 2 and 3. As can be seen by comparison of the predicted and experimental strength values, the specimens did not behave as expected. It was concluded that the laminates were resin rich due to the inadequate bleed caused by the central location of the graphite-epoxy. Additional (non-tapered) specimens were made with the composite as the outer adherend (Figures 18 and 19). The specimens with 70% scale laminates were

to reveal size and complexity effects and the 50% scale double lap specimens would be used to demonstrate similarity of shape parameters for simple and step-lap joints. The results are presented in Tables 2 and 3. Experimental strength compares well with the predicted value; however, partial peel failures were observed. To avoid this failure mode the laminates were reduced to 25% scale (Figure 20). This configuration was used to establish the data base for the simple specimen design for the remainder of the program.

2.4 Specimen Analysis

The methods used in the strength analyses are outlined in paragraphs 2.2.1 and 2.2.2. Adhesive properties are taken from Table 4 and Figure 21. Mechanical properties used for graphite-epoxy are presented in Table 5. Modulae of the layups on each step of these specimens were determined using computer program ABDMATM listed in Appendix C. Strength allowables for each of the specimens were determined by multiplying the corresponding modulae by the longitudinal strain allowable from Table 5. Properties used for titanium were taken from MIL-HDBK-5B.

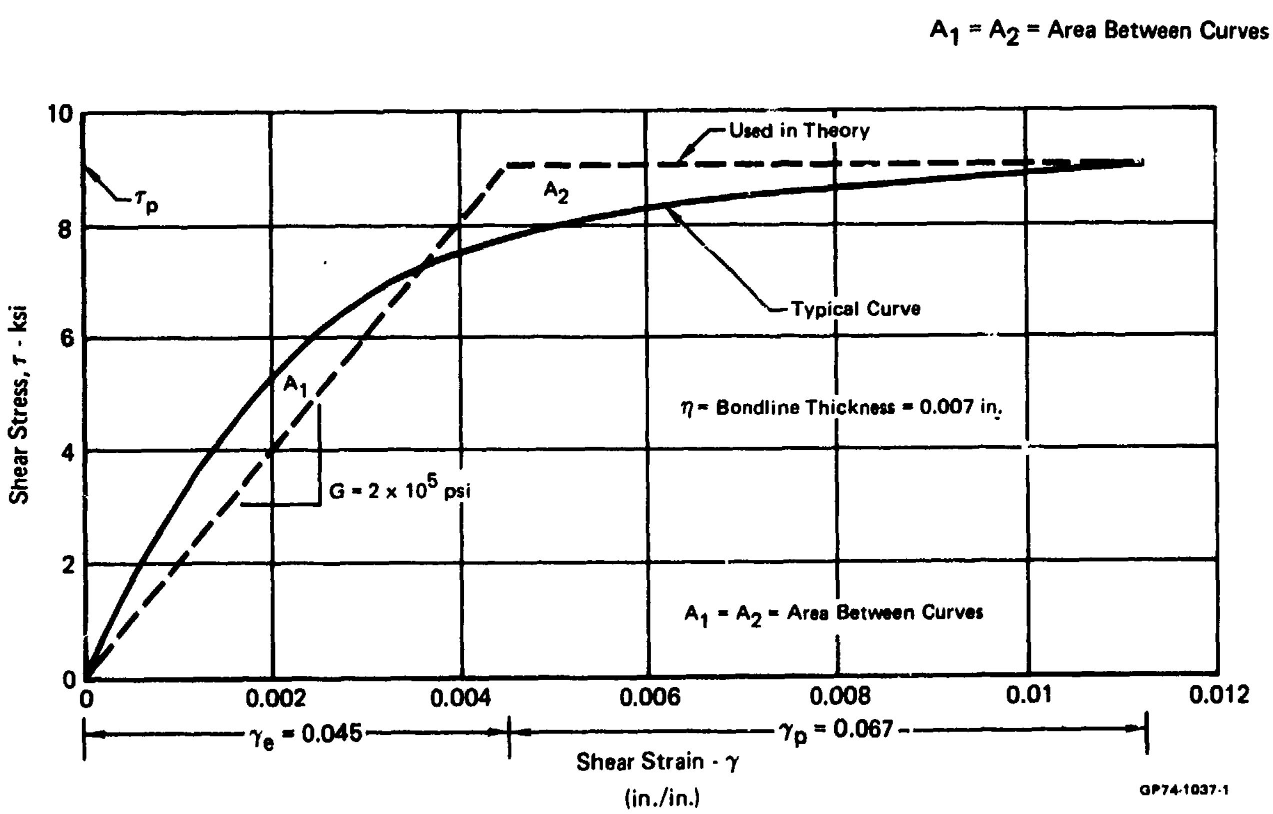

FIGURE 21 SHEAR STRESS STRAIN CURVE FOR ADHESIVE

TABLE 5 MECHANICAL PROPERTIES OF UNDIRECTIONAL NARMCO 5208/T300 GRAPHITE-EPOXY

Type Loading	Stress ksi	Modulus msi	Strain μ in./in.
0° Tension	200.7	22.3	9,000
90° Tension	7.8	1.95	4,000
0° Compression	267.8	20.6	13,000
90° Compression	48.7	3.6	13,500
0° - 90° Shear	10.6	1.0	23,000

$\nu_{12} = 0.21$

Per ply thickness = 0.0054 in.

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2.4.1 Step-Lap Specimen - Strength analysis of these specimens were accomplished with the aid of computer program A4EGX discussed and listed in Appendix A. The predicted strength of the full scale step-lap specimens is 17,629 (lb/in) with a cohesive failure in the adhesive initiating on the tang. The predicted strength of the 70% scale step-lap specimen is 12,341 (lb/in) with a cohesive failure initiating on the tang.

2.4.2 Simple Specimen (25% Double Lap) - The strength analysis of this specimen was accomplished using the procedure of paragraph 2.2.1. Figure 6 is entered with a value of $\lambda \ell$ equal to 14.75 and a γ_p/γ_e equal to 1.5. This gives a τ_{av}/τ_p equal to .25 and a strength of 5400 (lb/in). Thermal stresses were not considered. Experience indicates that for both ductile and brittle adhesives thermal stresses are usually relieved on double lap specimens by creep.

SECTION 3

SPECIMEN FABRICATION

The test specimens for this program were fabricated utilizing MCAIR process specifications and materials bought to MCAIR material specifications. The materials, fabrication procedures, and non-destructive testing (NDT) procedures are discussed in this section.

3.1 Materials

Three materials were used in specimen fabrication: graphite-epoxy, FM-400 adhesive, and titanium 6Al-4V.

3.1.1 Graphite-Epoxy - The graphite-epoxy was supplied as Rigidite 5208/T300 by Narmco Whittaker Materials Division, Cosa Mesa, California to meet MCAIR material specification MMS 548. The 50% scale double lap and the 50% scale tapered lap specimens (Figures 16 and 17) were made from Batch 174. The remainder of the specimens were made from Batch 149. Certified properties and/or MCAIR qualification test results for these batches are given in Table 6 together with the requirements of MMS-548.

3.1.2 FM-400 Adhesive - The adhesive film was supplied as FM-400 by American Cynamid Havre De Grace, Maryland to meet MCAIR material specification MMS-307 Type I and Type IV. Qualification data for the batches of adhesive used in the program and a comparison with specification properties are given in Table 7.

3.1.3 Titanium - The titanium details were fabricated from Ti-6Al-4V annealed sheet purchased to meet the requirement of MIL-T-9046 Type III Composition C.

3.2 Fabrication Procedures

Two procedures were used in the fabrication of these specimens: (1) initial procedure which was used early in the program and (2) a final procedure which was used to fabricate all the specimens for the reliability data base.

3.2.1 Initial Procedure - The first step in this procedure is the fabrication of titanium finger panels such as those illustrated in Figure 22. This concept was used to avoid machining of the titanium at the graphite-epoxy-to-titanium bond because burrs might be created on the titanium during maching, which could lead to a premature fatigue failure in the titanium. These finger panels were laid up with graphite-epoxy prepreg

TABLE 6 RESULTS OF GRAPHITE-EPOXY QUALIFICATION TESTS

Measured Property	MMS-548 Requirement	Batch 149	Batch 174
0° Tensile Stress (ksi)	180	227	230
0° Tensile Strain at Failure (micro in./in.)	–	10463	11092
0° Tensile Modulus (msi)	–	21.1	22.1
90° Tensile Stress (ksi)	8.0	8.0	10.2
90° Tensile Strain at Failure (micro in./in.)	4000	5800	5667
90° Tensile Modulus (msi)		2.3	2.0
Prepreg Resin Content (%)	39–44	37–43	38
Cured Resin Content (%)	–	30.4	–
Volatiles (%)	1.5	0.4	0.4
Resin Flow (%)	–	15.3	17

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TABLE 7 RESULTS OF FM-400 QUALIFICATION TESTS

Test Temperature (°F)	Lap Shear Strength		
	MMS-307 Requirement (psi)	Batch 162 Roll 579 (psi)	Batch 150 Roll 510 (psi)
RT	3000	3820	3547
365	2400	2540	2593
420	1500	2063	2210

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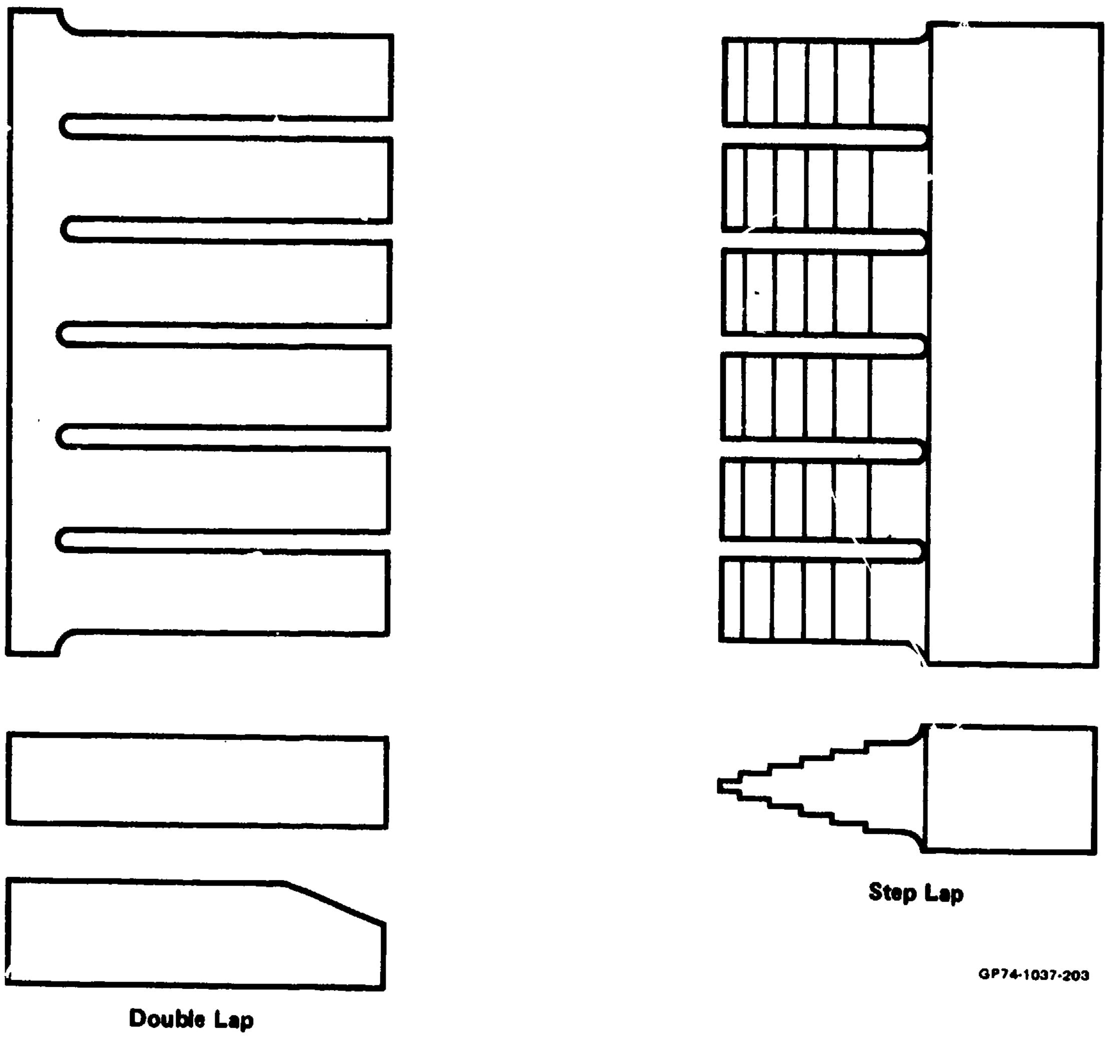


FIGURE 22 TITANIUM FINGER PANELS

and other details as shown in Figure 23. Step lap specimens were laid-up in the conventional manner shown in Figure 24. Both types of lap specimens were laid up on a tooling plate, using shims to support the specimens, and then bagged. After curing, the individual specimens were cut out of the panels. This fabrication procedure proved to be expensive and a better way was found to fabricate the specimens as discussed below.

3.2.2 Final Procedure - Layup procedures were modified to eliminate the tooling plate and associated shimming by utilizing a double bag and picture frame holder. Pressure plates were used to maintain flatness. The finger panel concept was discarded in favor of machining the graphite-epoxy-to-titanium interface using diamond wheel slicing followed by grinding. The grinding operation removed any burrs on the titanium. These procedures are detailed as follows:

Simple specimens were fabricated to the specification of Figure 25 according to the procedures listed below:

(1) Panel assemblies, designed to provide ten simple specimens per assembly were assembled according to the requirements shown and noted in Figure 26.

(2) Each assembly was then placed in the layup configuration shown and noted in Figure 27.

(3) The vacuum bag was placed in an autoclave and connected to the autoclave vacuum system.

(4) Pressure in the vacuum bag was reduced to less than 0.1 inches of mercury.

(5) Autoclave was pressurized to 50 psig.

(6) Vacuum bag was checked for leaks.

(7) Autoclave pressure was reduced to 10 psig.

(8) Pressure in the vacuum bag was increased to 18-19 inches of mercury.

(9) Assemblies were heated to 270°F at a rate of 3-5°F per minute.

(10) Assemblies were maintained at 270°F for 30 minutes (the 30 minutes hold was started when assemblies reached 275°F).

(11) Autoclave was pressurized to 85 psig.

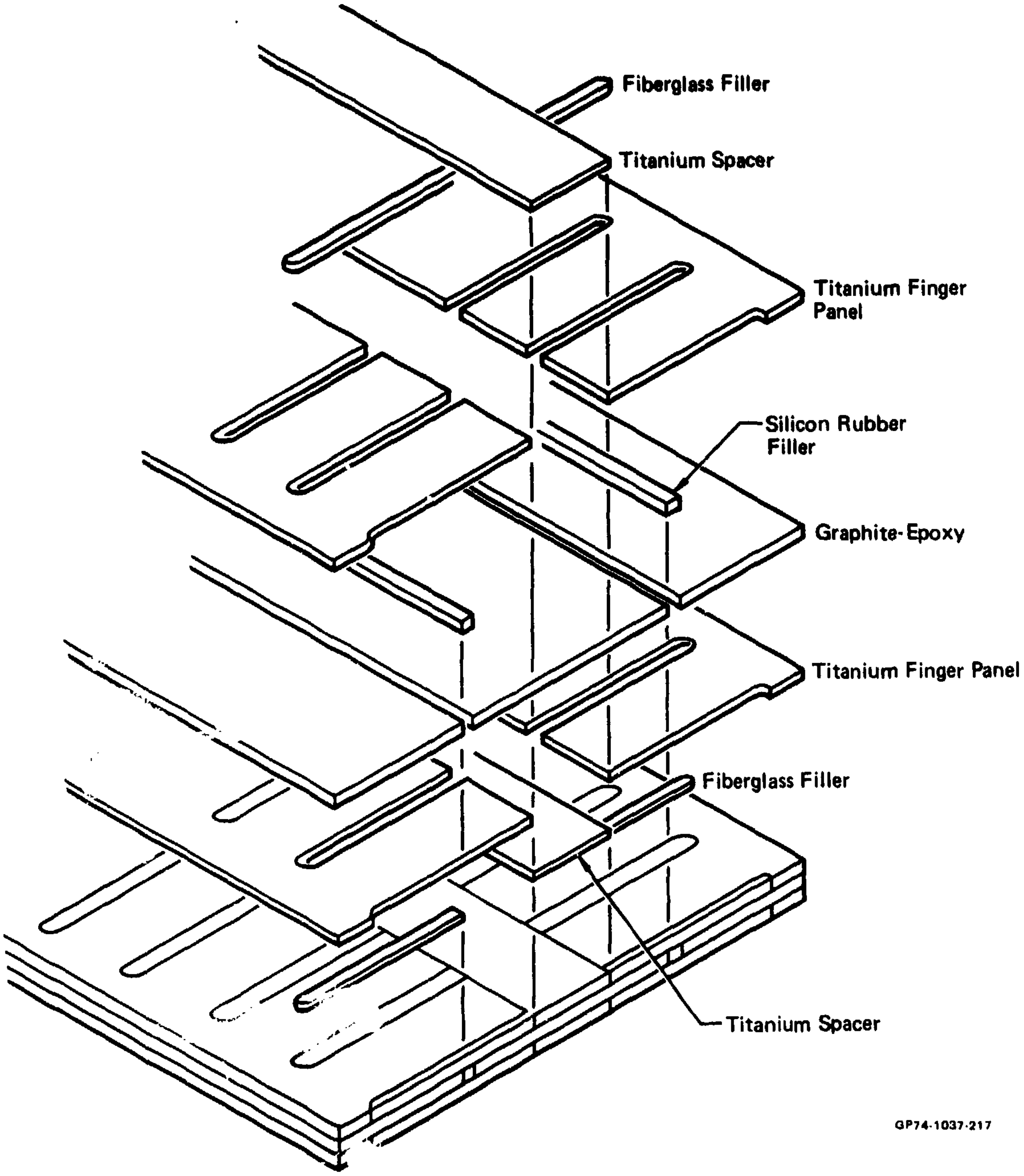


FIGURE 23 LAY-UP SEQUENCE FOR DOUBLE AND TAPERED LAP SPECIMENS

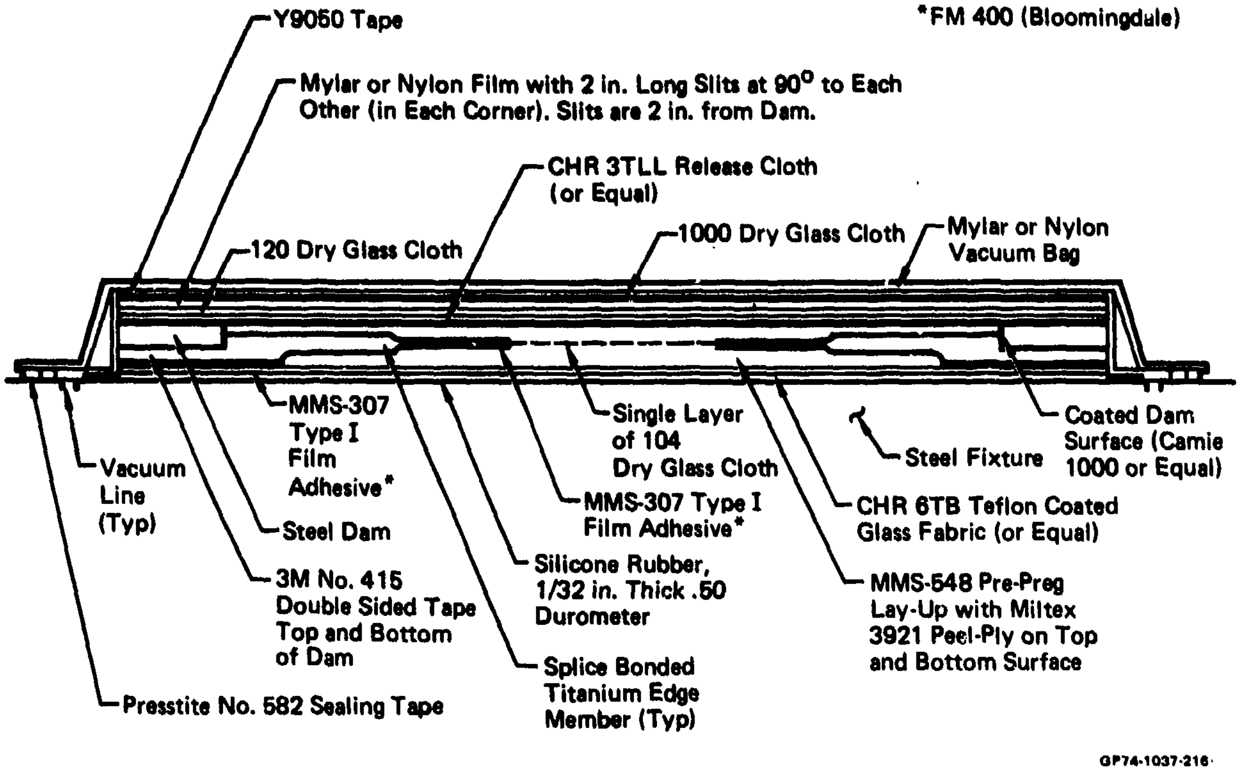
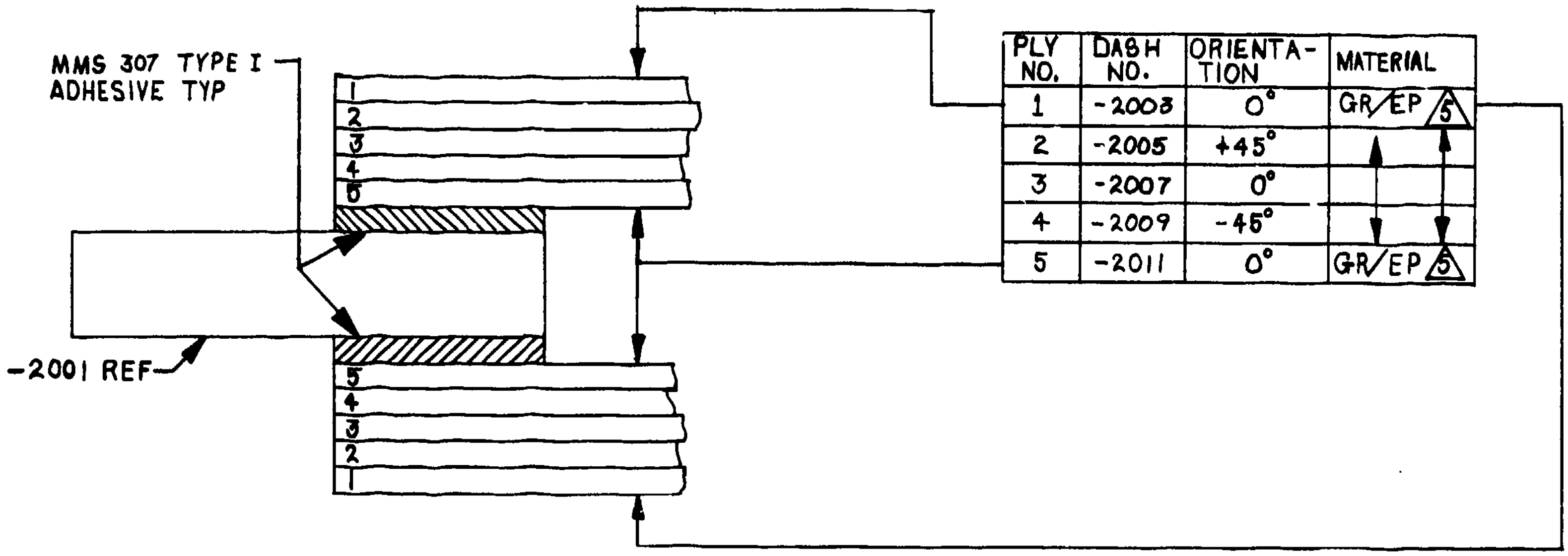


FIGURE 24 INITIAL LAY-UP FOR STEP LAP SPECIMENS



PLY NO.	DASH NO.	ORIENTATION	MATERIAL
1	-2003	0°	GR/EP 5
2	-2005	+45°	
3	-2007	0°	
4	-2009	-45°	
5	-2011	0°	GR/EP 5

SECTION A-A

SCALE : NONE

9. Penetrant inspect -2001 per PS 21202
8. Material shall be free of Alpha case; shall be cleaned and primed per PS 12037 and primed per PS 14130
7. Break sharp edges per PS 23041 on -2001
6. Surface roughness 125 RHR or better for -2001
5. Graphite/epoxy material per MMS 548 Rev A Amend I (NARMCO 5208/THORNEL 300)
4. Fabricate and bond per PS 14240 PB 4-258 (COCURE).
3. Graphite/epoxy cured ply thickness: 0.0054 ± 0.0003
2. Last section letter used: A
1. Marking per PS 16001

Notes:

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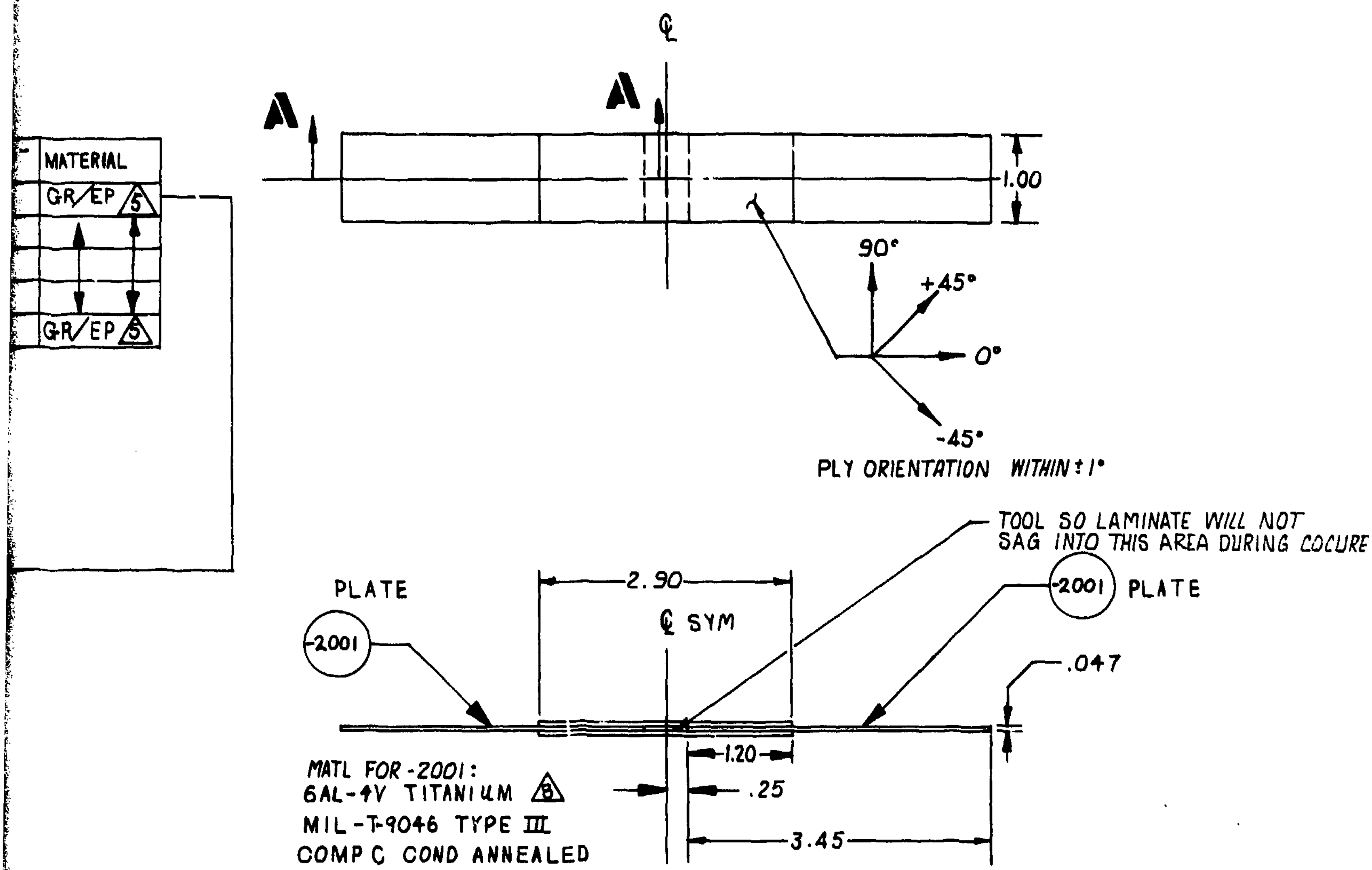
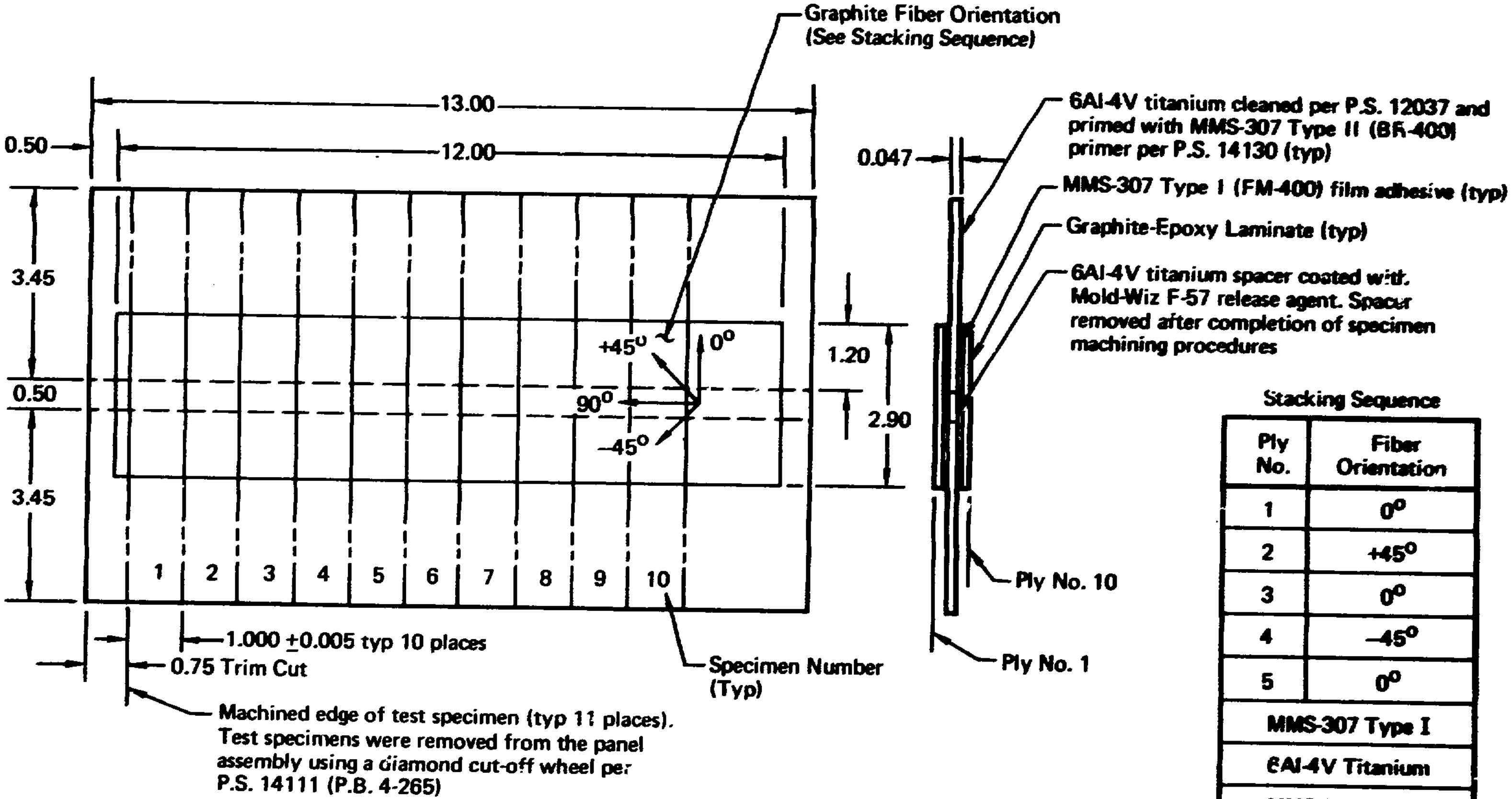
FIGURE 25. SIMPLE SPECIMEN DRAWING



-1001
SCALE-1/1



Stacking Sequence

Ply No.	Fiber Orientation
1	0°
2	+45°
3	0°
4	−45°
5	0°
MMS-307 Type I	
6Al-4V Titanium	
MMS-307 Type I	
6	0°
7	+45°
8	0°
9	−45°
10	0°

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FIGURE 26 SIMPLE JOINT PANEL ASSEMBLY AND SPECIMEN MACHINING REQUIREMENTS

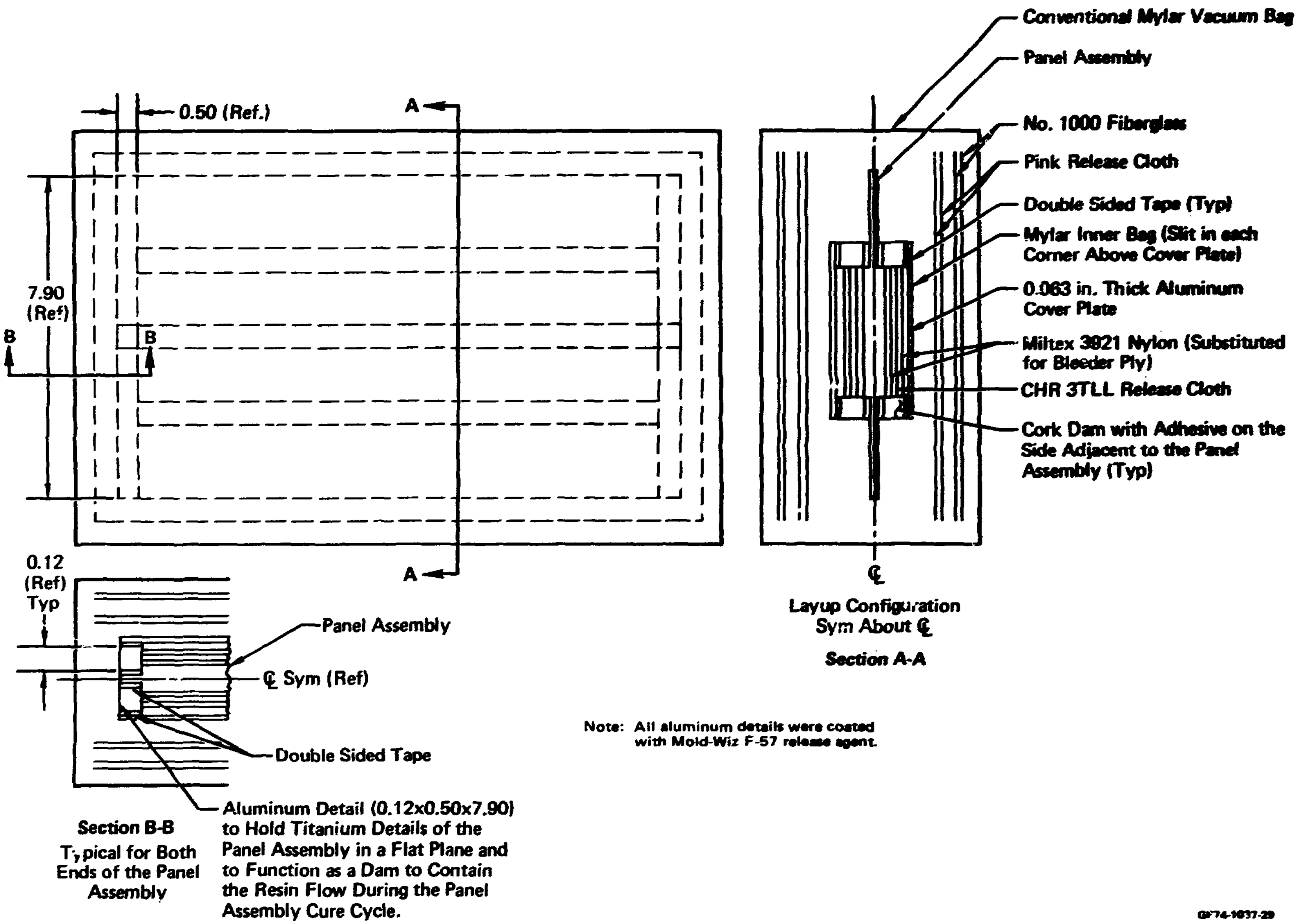


FIGURE 27 SIMPLE JOINT PANEL ASSEMBLY LAYUP CONFIGURATION

(12) Vacuum bag was vented to atmospheric pressure when autoclave pressure reached 25 psig. Vacuum bag was not back filled.

(13) Assemblies were heated to 350°F at a rate of 3-5°F per minute.

(14) Assemblies were maintained at 350°F for 120 minutes.

(15) Assemblies were cooled to 150°F, or less, while maintaining full autoclave pressure.

(16) Vacuum bag was disconnected from the autoclave vacuum system and vacuum bag was removed from the autoclave.

(17) Assemblies were removed from vacuum bag.

(18) Assemblies were removed from layup configuration.

(19) Assemblies were placed in a cool air circulating oven.

(20) Assemblies were heated to 350°F at a rate of 3-6°F per minute.

(21) Assemblies were maintained at 350°F for 8 hours.

(22) Assemblies were cooled to 150°F.

(23) Assemblies were removed from the oven.

(24) Assemblies were machined into simple specimens in accordance with requirements shown and noted in Figure 26.

(25) The nylon peel ply was removed from the graphite-epoxy laminate portions of each test specimen.

A completed panel assembly and a completed simple specimen is in the photograph, Figure 28.

The small scale step-lap specimens (Figure 13) were fabricated to the specifications of Figure 29 according to the procedure listed below:

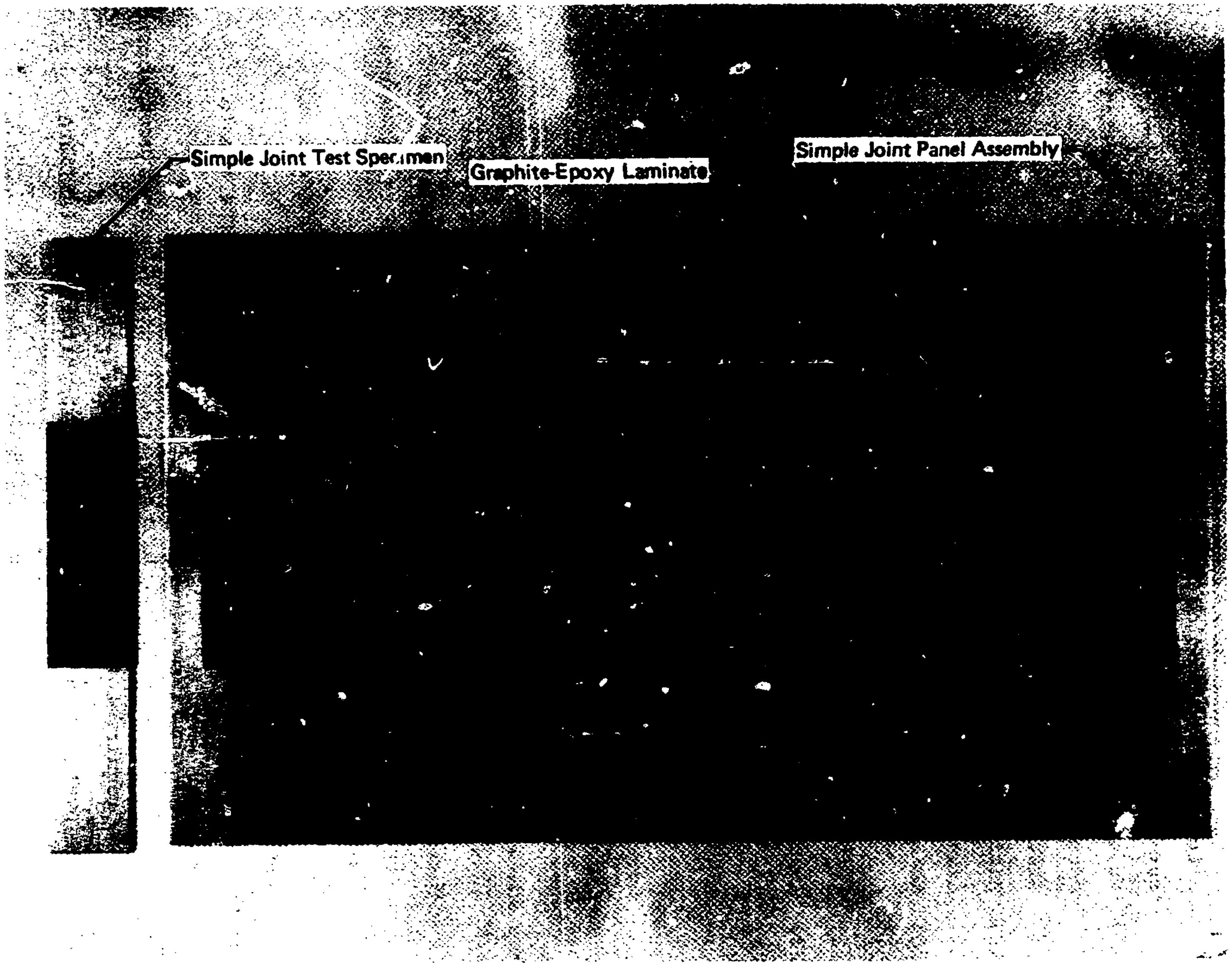
(1) Panel assemblies, designed to provide 10 small scale step-lap specimens per assembly, were assembled according to requirements shown and noted in Figure 30.

(2) Each assembly was placed in the layup configuration shown and noted in Figure 31.

(3) thru (23) Same as procedures (3) through (23) for the simple specimens.

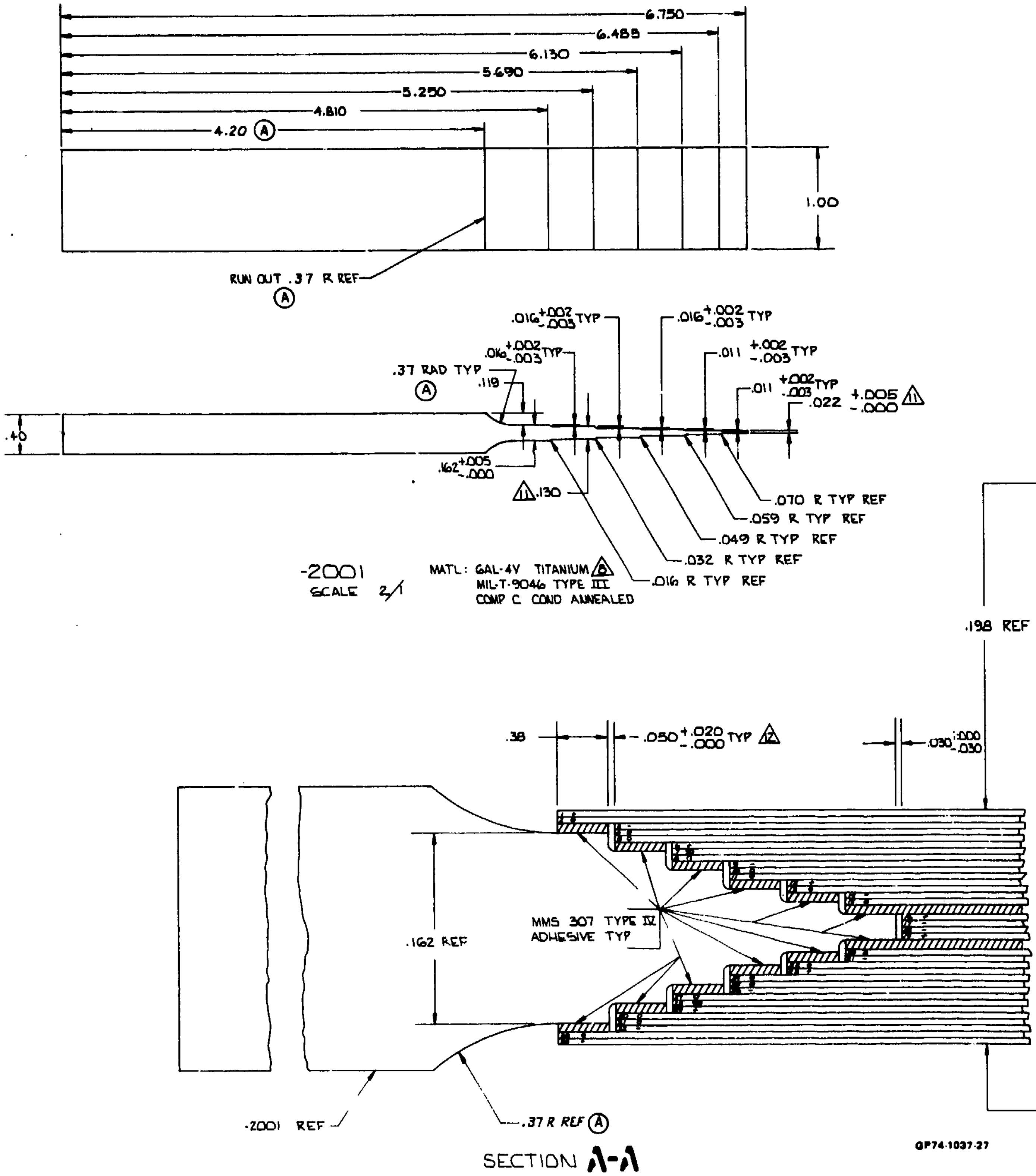
(24) Assemblies were machined into small scale step-lap specimens according to requirements shown and noted in Figure 32.

(25) Nylon peel ply was removed from the graphite-epoxy laminate portions of each test specimen.



GP74-1037-36

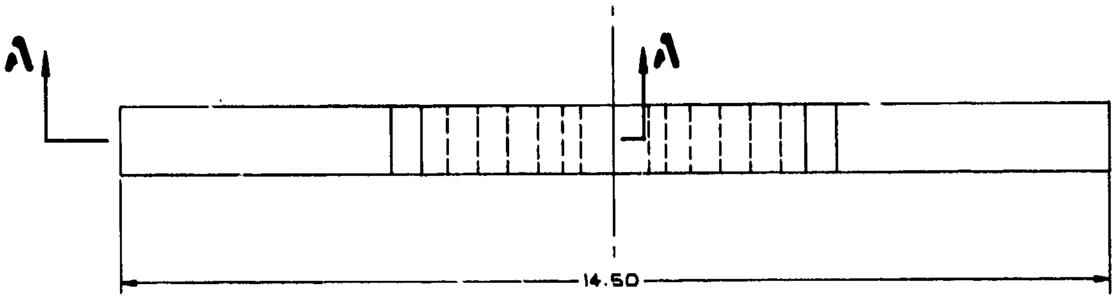
FIGURE 28 COMPLETED SIMPLE JOINT PANEL ASSEMBLY AND TEST SPECIMEN

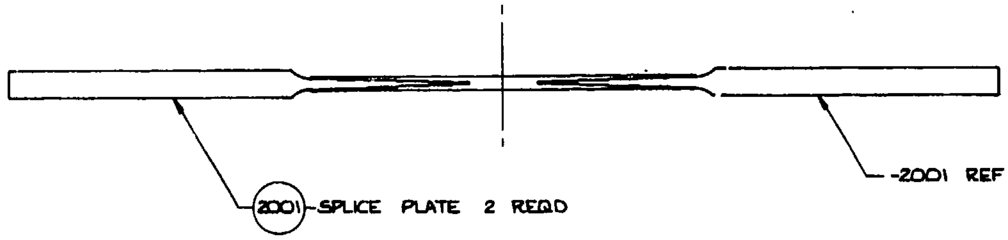


PLY NO	DASH NO	ORIENTATION
1	-2003	+45°
2	-2005	0°
3	-2007	-45°
4	-2009	0°
5	-2011	0°
6	-2013	+45°
7	-2015	90°
8	-2017	0°
9	-2019	-45°
10	-2021	0°
11	-2023	0°
12	-2025	+45°
13	-2027	0°
14	-2029	-45°
15	-2031	0°
16	-2033	+45°
17	-2035	-45°
18	-2037	-45°
19	-2039	+45°
20	-2041	0°
21	-2043	-45°
22	-2045	0°
23	-2047	+45°
24	-2049	0°
25	-2051	0°
26	-2053	-45°
27	-2055	0°
28	-2057	90°
29	-2059	+45°
30	-2061	0°
31	-2063	0°
32	-2065	-45
33	-2067	0°
34	-2069	+45

FIGURE 29. SMALL SCALE STEP-LAP SPECIMEN DRAWING

REVISIONS				
SYM	ZONE	DESCRIPTION	DATE	APPROVED
A		.37R TYP WAS 1.00R TYP, 4.20 WAS 4.00	[illegible]	[illegible]





PLY NO	DASH NO	ORIENTATION	MATERIAL
1	-2003	+45°	GR/EP 10
2	-2005	0°	
3	-2007	-45°	
4	-2009	0°	
5	-2011	0°	
6	-2013	+45°	
7	-2015	90°	
8	-2017	0°	
9	-2019	-45°	
10	-2021	0°	
11	-2023	0°	
12	-2025	+45°	
13	-2027	0°	
14	-2029	-45°	
15	-2031	0°	
16	-2033	+45°	
17	-2035	-45°	
18	-2037	-45°	
19	-2039	+45°	
20	-2041	0°	
21	-2043	-45°	
22	-2045	0°	
23	-2047	+45°	
24	-2049	0°	
25	-2051	0°	
26	-2053	-45°	
27	-2055	0°	
28	-2057	90°	
29	-2059	+45°	
30	-2061	0°	
31	-2063	0°	
32	-2065	-45°	
33	-2067	0°	
34	-2069	+45°	GR/EP 10

-1001

12. Tolerance applies to first ply on step, tolerance for remaining plies is +0.060 – 0.030
11. Accumulation of tolerances by step height dimensions to be controlled by end dimensions
10. Graphite/epoxy material per MMS 548 rev A Amend I (NARMCO 5208/THORNEL 300)
9. Penetrant inspect -2001 per PS 21202, Class A in step areas; all other areas Class C
8. Material shall be free of Alpha case; shall be cleaned per PS 12037 and primed per PS 14130
7. Break sharp edges per PS 23041 on -2001
6. Surface roughness 125 RHR or better for -2001
5. Chem mill per PS 20022
4. Fabricate and bond per PS 14240 PB 4-258
3. Graphite/epoxy cured ply thickness: 0.0054 ± 0.0003
2. Last section letter used: A
1. Marking per PS 16001

Notes:

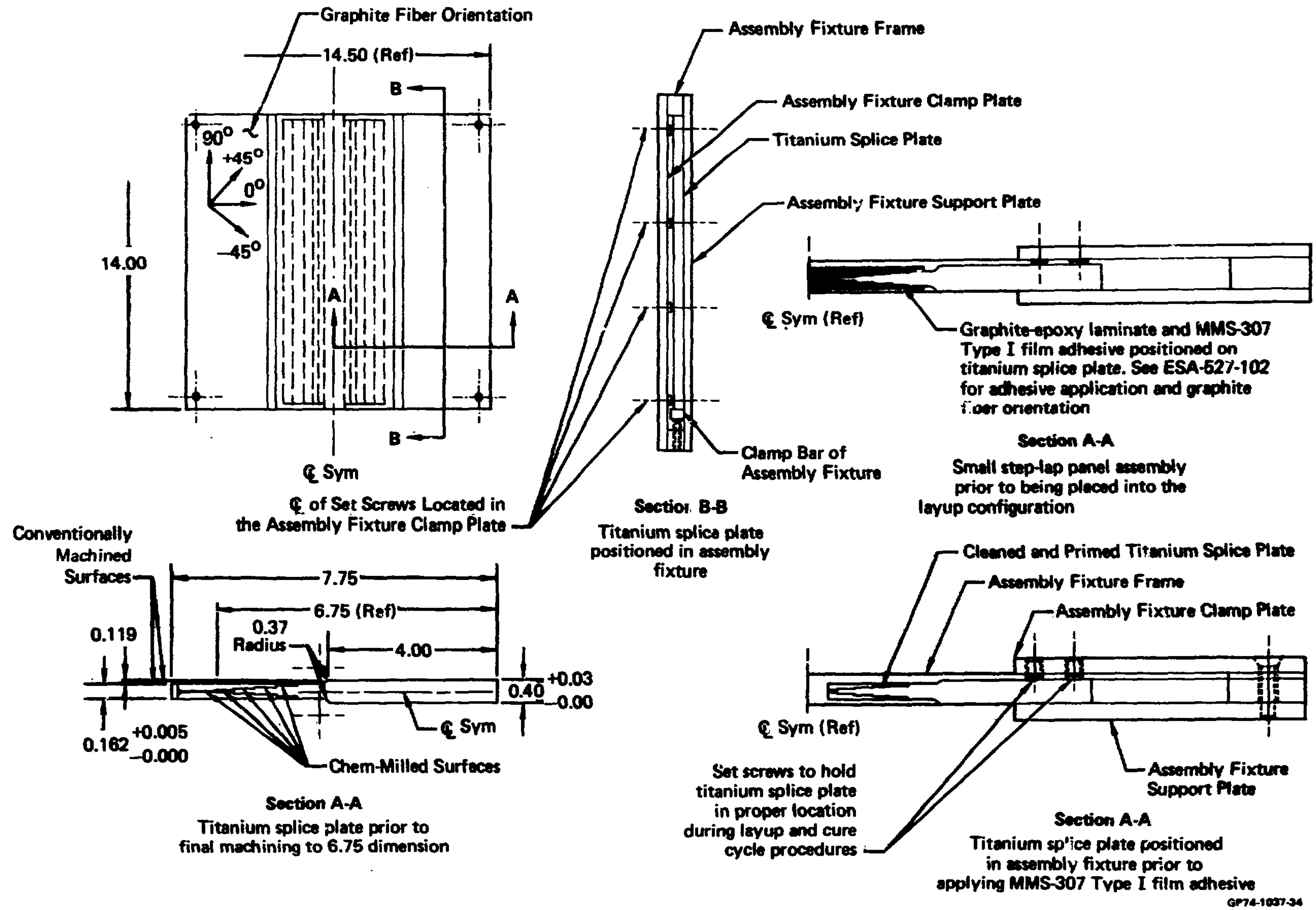


FIGURE 30 SMALL SCALE STEP-LAP PANEL ASSEMBLY

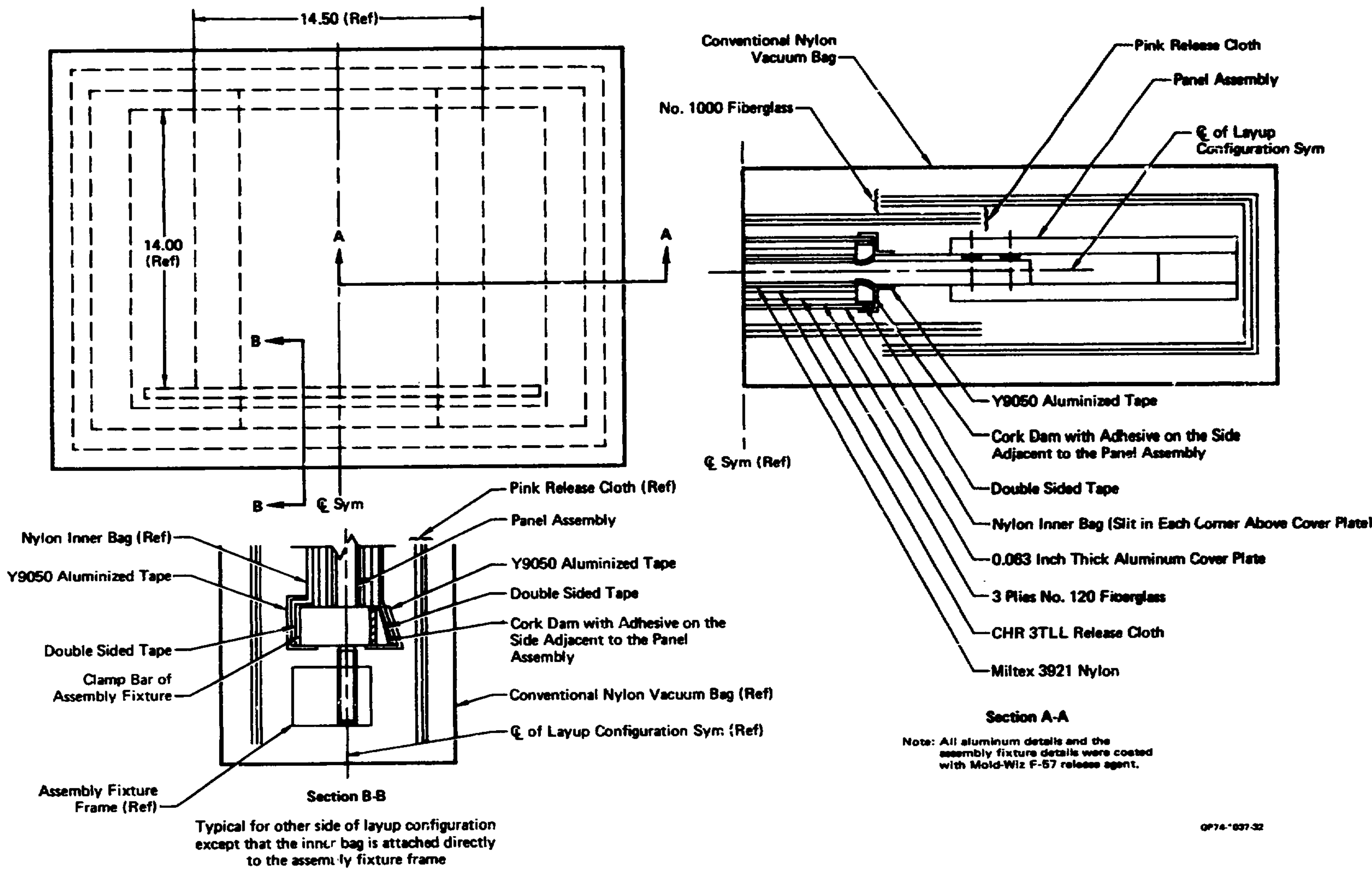


FIGURE 31 SMALL SCALE STEP-LAP LAYUP CONFIGURATION

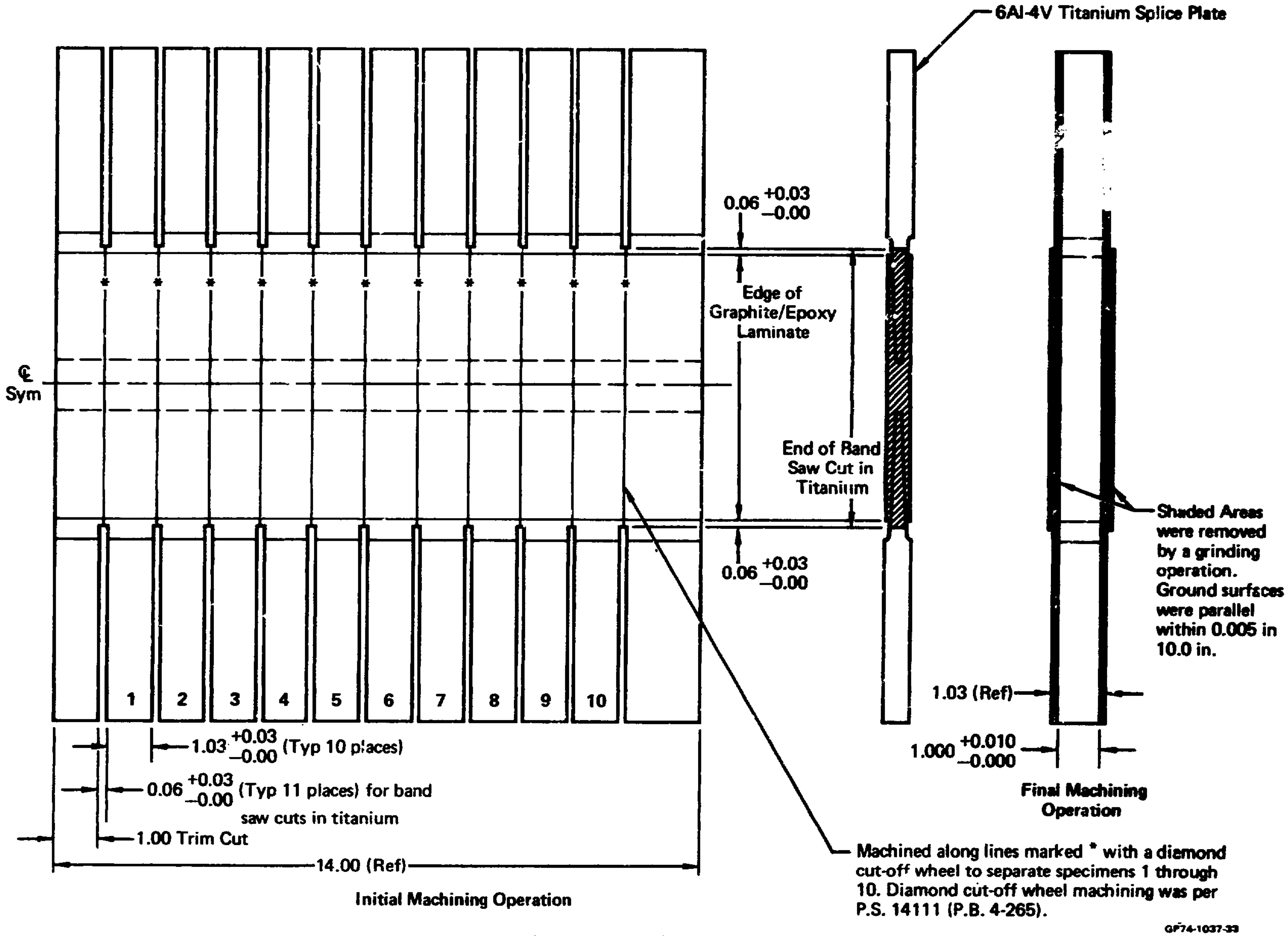


FIGURE 32 MACHINING REQUIREMENTS FOR SMALL SCALE STEP-LAP AND FULL SCALE STEP-LAP PANEL ASSEMBLIES

A completed panel assembly and a completed small scale step-lap specimen is shown in Figure 33. A completed panel assembly which has been bandsawed prior to being machined with a diamond cut-off wheel is shown in Figure 34.

The full scale step-lap specimens (Figure 11) were fabricated to the specifications of Figure 35 according to the procedures listed below:

(1) Panel assemblies, designed to provide 10 intermediate scale step-lap specimens per assembly, were assembled according to requirements shown and noted in Figure 36.

(2) Each assembly then was placed in the layup configuration shown and noted in Figure 37.

(3) thru (23) Same as procedures (3) through (23) for the simple specimens.

(24) Assemblies were machined into step-lap specimens according to requirements shown and noted in Figure 38.

(25) Nylon peel ply was removed from the graphite-epoxy laminate portions of each specimen.

A series of photographs showing a full scale step-lap assembly in various stages of assembly are shown in Figures 39 through 45.

Thickness and width measurements of each test specimen fabricated for this test program were determined according to requirements shown and noted in Figure 46.

Test specimens designated for static testing at room temperature were instrumented according to requirements shown and noted in Figure 47. Table 8 identifies in which autoclave runs the specimens were cured.

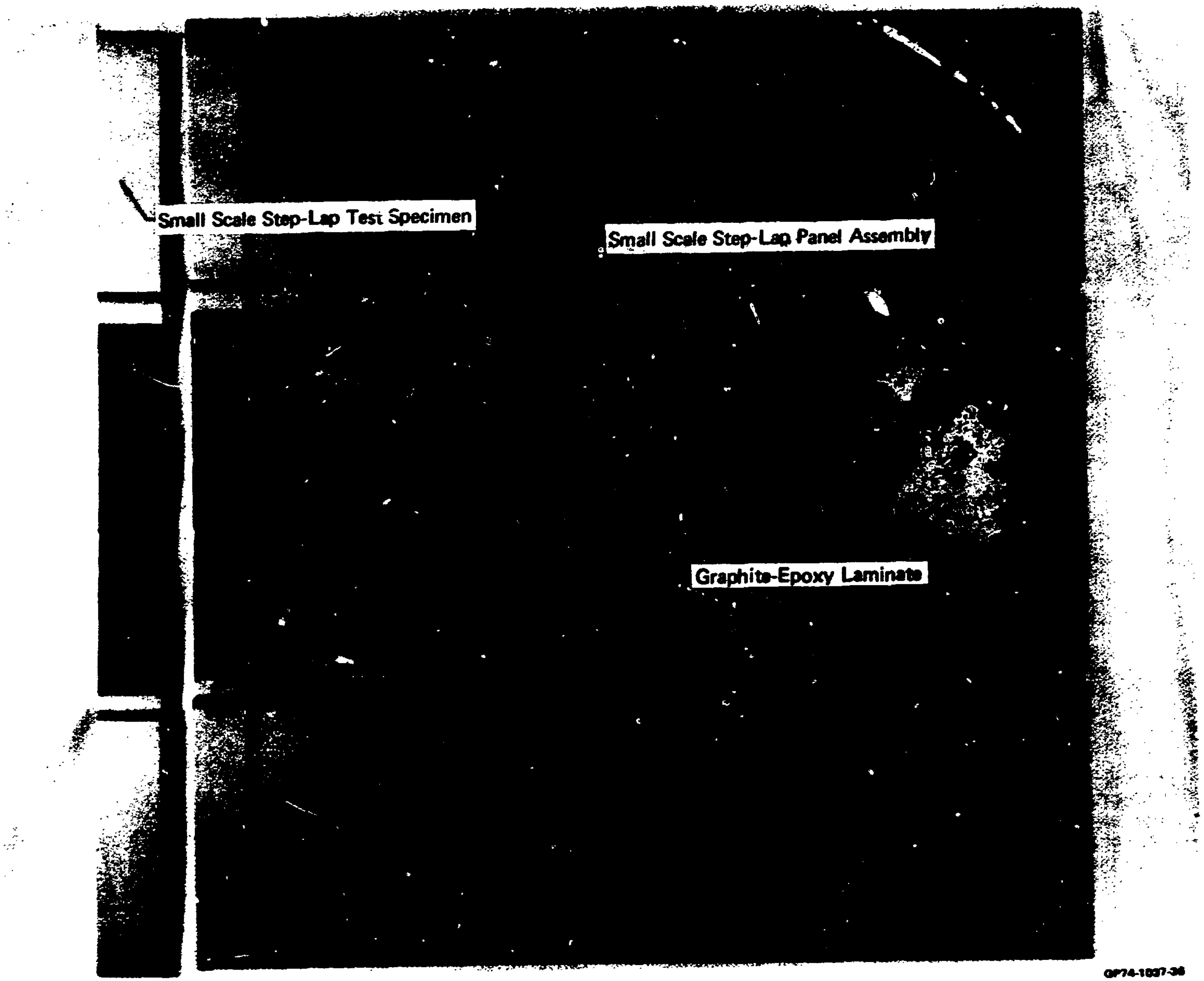


FIGURE 33 COMPLETED SMALL SCALE STEP-LAP PANEL ASSEMBLY AND TEST SPECIMEN

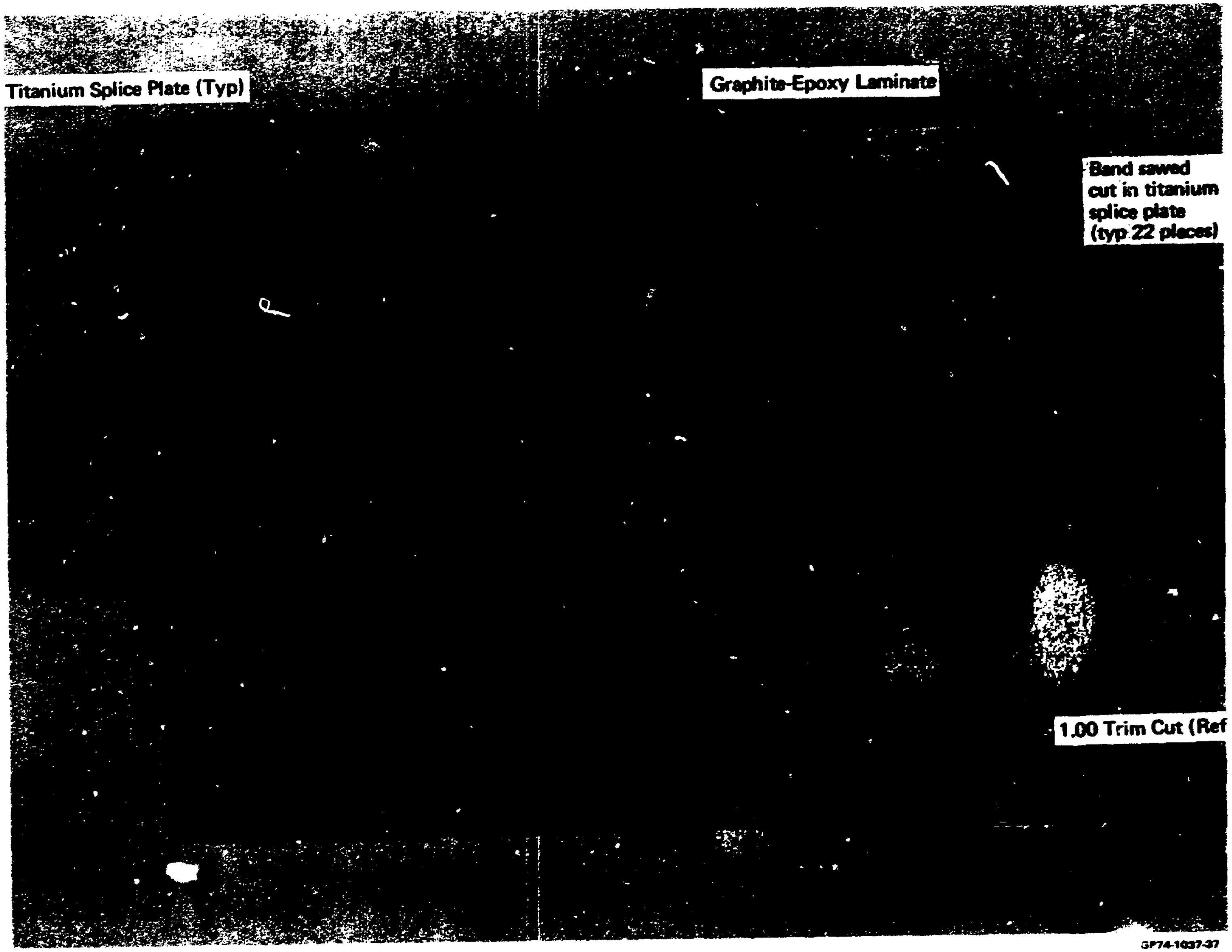


FIGURE 34 COMPLETED SMALL SCALE STEP-LAP PANEL ASSEMBLY PRIOR TO BEING MACHINED WITH A DIAMOND CUT-OFF WHEEL

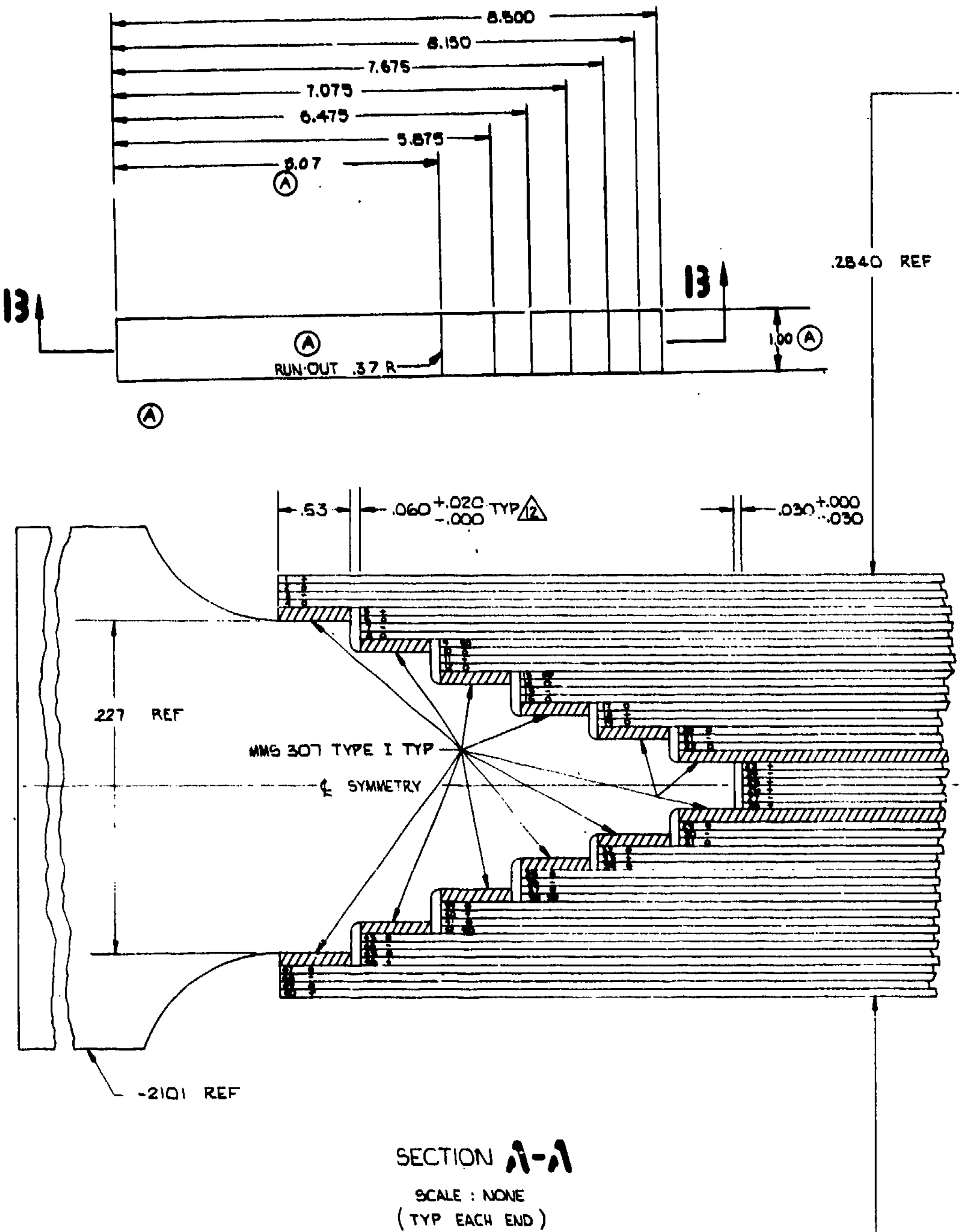


TABLE I

PLY NO	DASH NO	ORIENTATION	MATERIAL
1	-2001	+45°	GR/EP 10
2	-2003	0°	
3	-2005	-45°	
4	-2007	0°	
5	-2009	+45°	
6	-2011	0°	
7	-2013	-45°	
8	-2015	0°	
9	-2017	90°	
10	-2019	0°	
11	-2021	+45°	
12	-2023	0°	
13	-2025	90°	
14	-2027	0°	
15	-2029	-45°	
16	-2031	0°	
17	-2033	0°	
18	-2035	+45°	
19	-2037	0°	
20	-2039	0°	
21	-2041	-45°	
22	-2043	0°	
23	-2045	+45°	
24	-2047	-45°	
25	-2049	+45°	
26	-2051	+45°	
27	-2053	-45°	
28	-2055	+45°	
29	-2057	0°	
30	-2059	-45°	
31	-2061	0°	
32	-2063	0°	
33	-2065	+45°	
34	-2067	0°	
35	-2069	0°	
36	-2071	-45°	
37	-2073	0°	
38	-2075	90°	
39	-2077	0°	
40	-2079	+45°	
41	-2081	0°	
42	-2083	90°	
43	-2085	0°	
44	-2087	-45°	
45	-2089	0°	
46	-2091	+45°	
47	-2093	0°	
48	-2095	-45°	
49	-2097	0°	
50	-2099	+45°	GR/EP 10

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FIGURE 35. FULL SCALE STEP-LAP SPECIMEN DRAWING

TABLE I

PLY NO	DASH NO	ORIENTATION	MATERIAL
1	-2001	+45°	GR/EP 10
2	-2003	0°	
3	-2005	-45°	
4	-2007	0°	
5	-2009	+45°	
6	-2011	0°	
7	-2013	-45°	
8	-2015	0°	
9	-2017	90°	
10	-2019	0°	
11	-2021	+45°	
12	-2023	0°	
13	-2025	90°	
14	-2027	0°	
15	-2029	-45°	
16	-2031	0°	
17	-2033	0°	
18	-2035	+45°	
19	-2037	0°	
20	-2039	0°	
21	-2041	-45°	
22	-2043	0°	
23	-2045	+45°	
24	-2047	-45°	
25	-2049	+45°	
26	-2051	+45°	
27	-2053	-45°	
28	-2055	+45°	
29	-2057	0°	
30	-2059	-45°	
31	-2061	0°	
32	-2063	0°	
33	-2065	+45°	
34	-2067	0°	
35	-2069	0°	
36	-2071	-45°	
37	-2073	0°	
38	-2075	90°	
39	-2077	0°	
40	-2079	+45°	
41	-2081	0°	
42	-2083	90°	
43	-2085	0°	
44	-2087	-45°	
45	-2089	0°	
46	-2091	+45°	
47	-2093	0°	
48	-2095	-45°	
49	-2097	0°	
50	-2099	+45°	GR/EP 10

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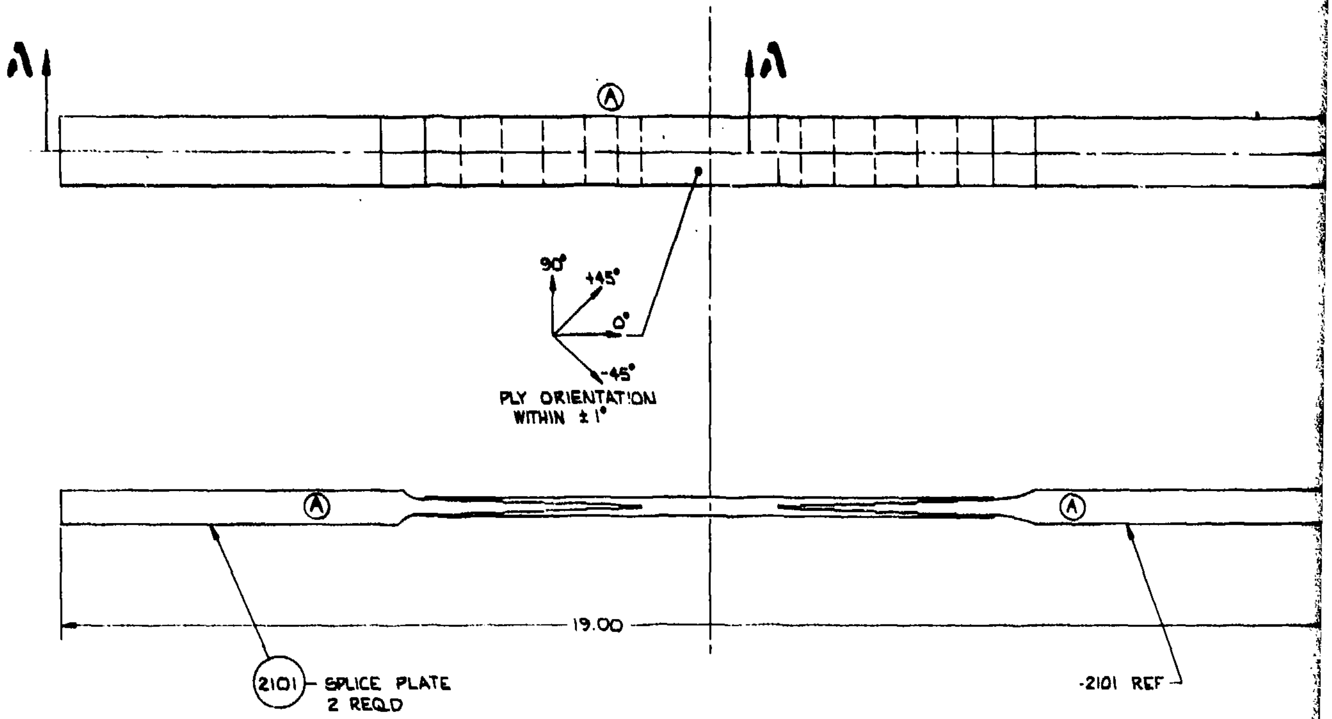
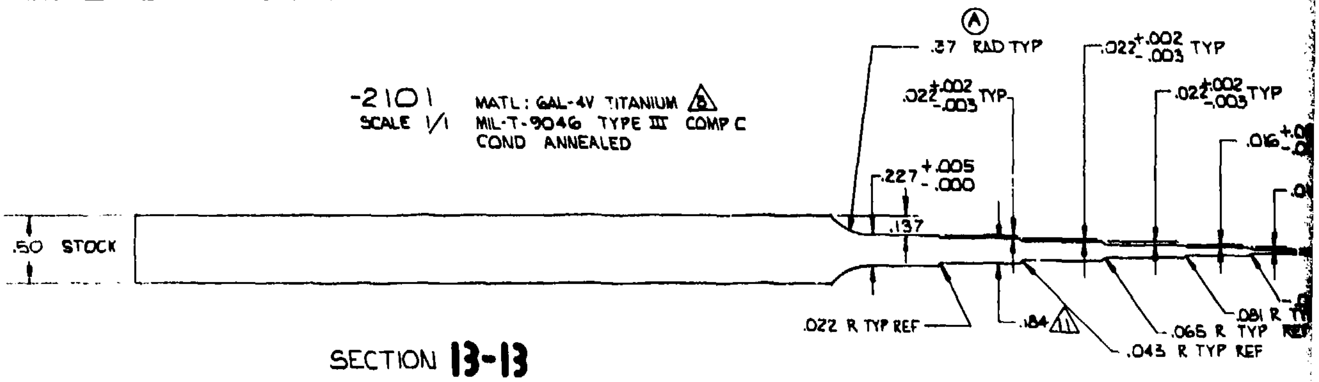


-1001



-2101 SCALE 1/1

MATL: 6AL-4V TITANIUM 8
MIL-T-9046 TYPE III COMP C
COND ANNEALED

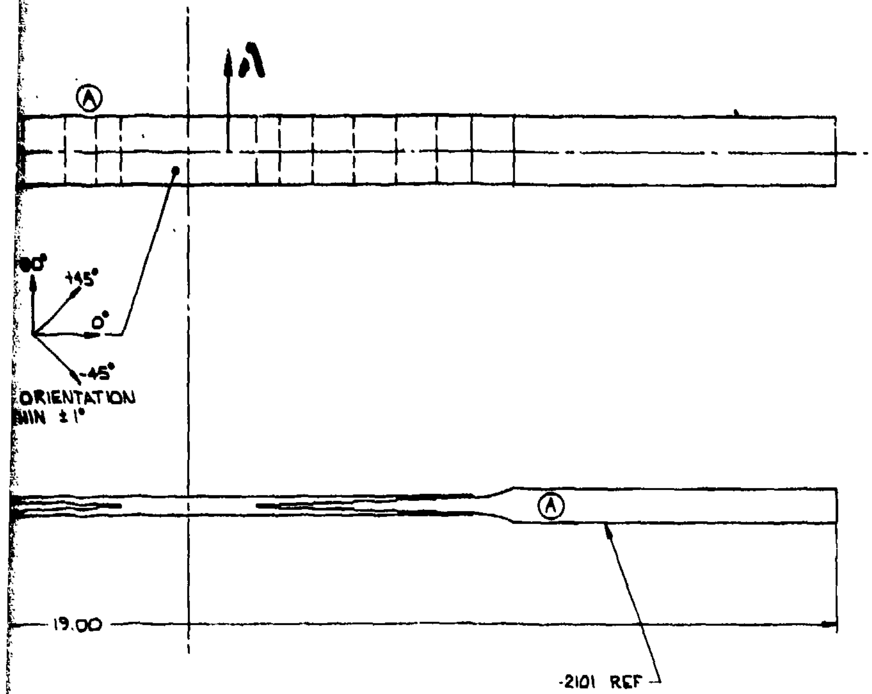
SECTION B-B
SCALE 2/1

A 13
12 Tolerance applies to first ply on step, toler
11 Accumulation of tolerances by step height
10 Graphite/epoxy material per MMS 548 Rev
A 9. Penetrant inspect -2101 per PS 21202, Cl
8 Material shall be free of Alpha case; shall b
A 7. Break sharp edges per PS 23041 on -2101
A 6. Surface roughness 125 RHR or better for -2
5. Chem mill -2101 per PS 20022
4. Fabricate and bond per PS 14240 PB 4-25
3. Graphite/epoxy cured ply thickness: 0.00
2. Last section letter used: B
1. Marking per PS 16001

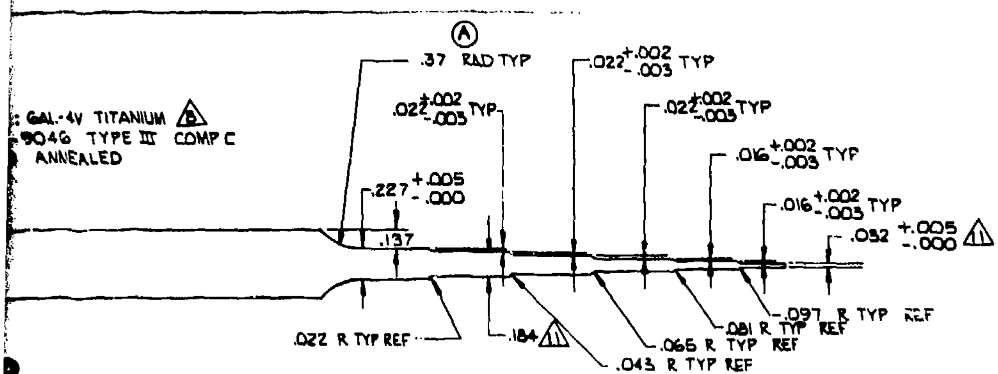
Notes:

REVISIONS				
SYM	ZONE	DESCRIPTION	DATE	APPROVED
A		.37 R TYP WAS 1.50R TYP 5.07 WAS 4.72; NOTE 13 DELETED ON -2101 GRIPS WERE 4.00, NOW 1.00 ON -2101 WIDTH IS 1.00, WAS 2.00 FOLLOWING DASH NOS. ARE OBSOLETED: -1005, -2103, 2105, 2107, -2109, -2111, 2113, -2115, 2117, -2119, 2121, 2123, 2125, 2127, -2129, 2131, 2133, 2135, 2137, -2139, 2141 2143, 2145, 2147, 2149, 2151, 2153.	8-7-74	J.E. COLLI

OBSOLETE -1003 (A)



-1001



(A) 13.

12. Tolerance applies to first ply on step, tolerance for remaining plies is +0.000 – 0.030

11. Accumulation of tolerances by step height dimensions to be controlled by end dimensions

10. Graphite/epoxy material per MMS 548 Rev A Amend I (NARMCO 5208/THORNEL 300)

(A) 9. Penetrant inspect -2101 per PS 21202, Class A in step areas; all other areas Class C

8. Material shall be free of Alpha case; shall be cleaned per PS 12037 and primed per PS 14130

(A) 7. Break sharp edges per PS 23041 on -2101

(A) 6. Surface roughness 125 RHR or better for -2101

5. Chem mill -2101 per PS 20022

4. Fabricate and bond per PS 14240 PB 4-258

3. Graphite/epoxy cured ply thickness: 0.0054 ± 0.0003

2. Last section letter used: B

1. Marking per PS 16001

Notes:

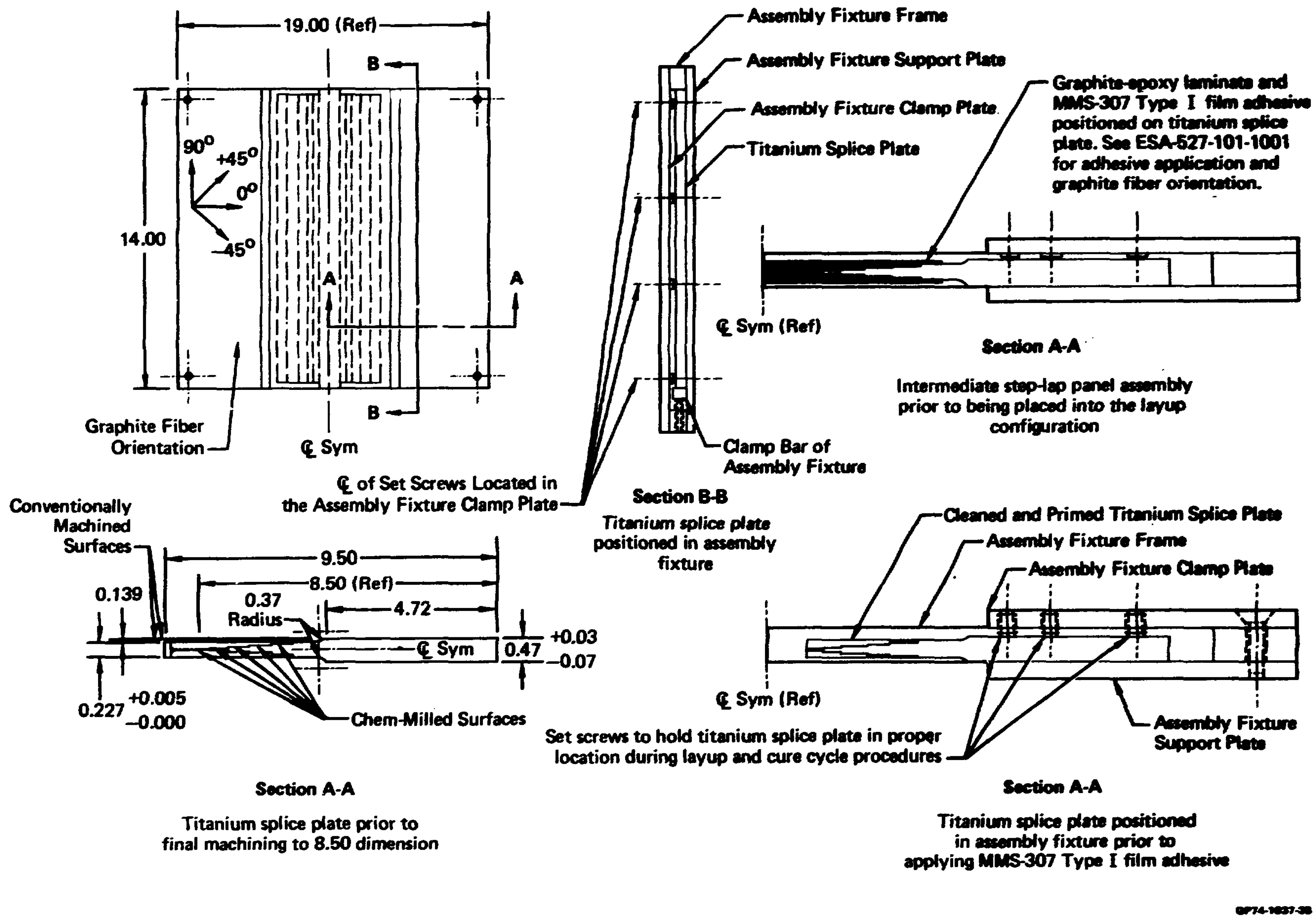


FIGURE 36 FULL SCALE STEP-LAP PANEL ASSEMBLY

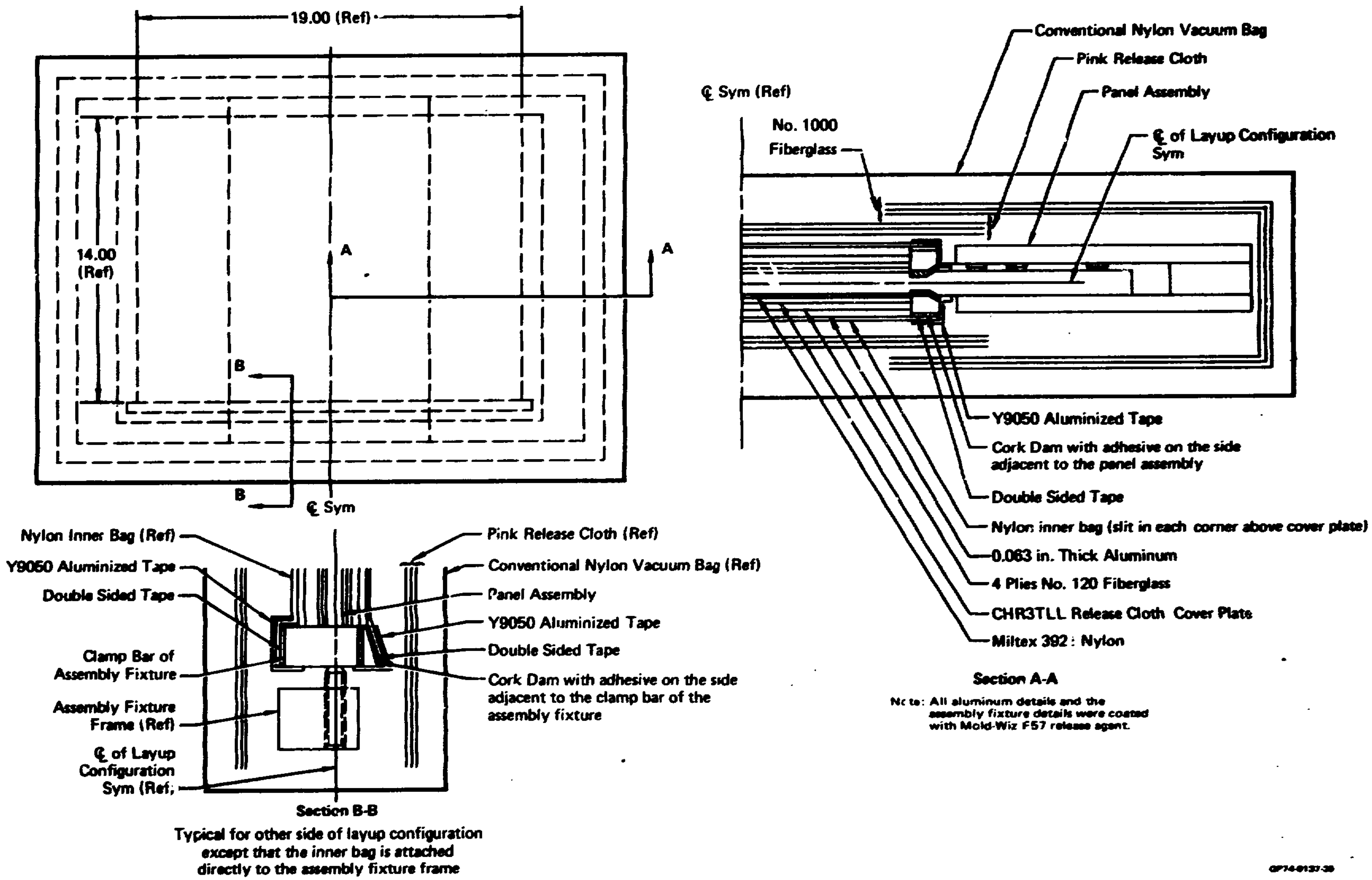


FIGURE 37 FULL SCALE STEP-LAP LAYUP CONFIGURATION

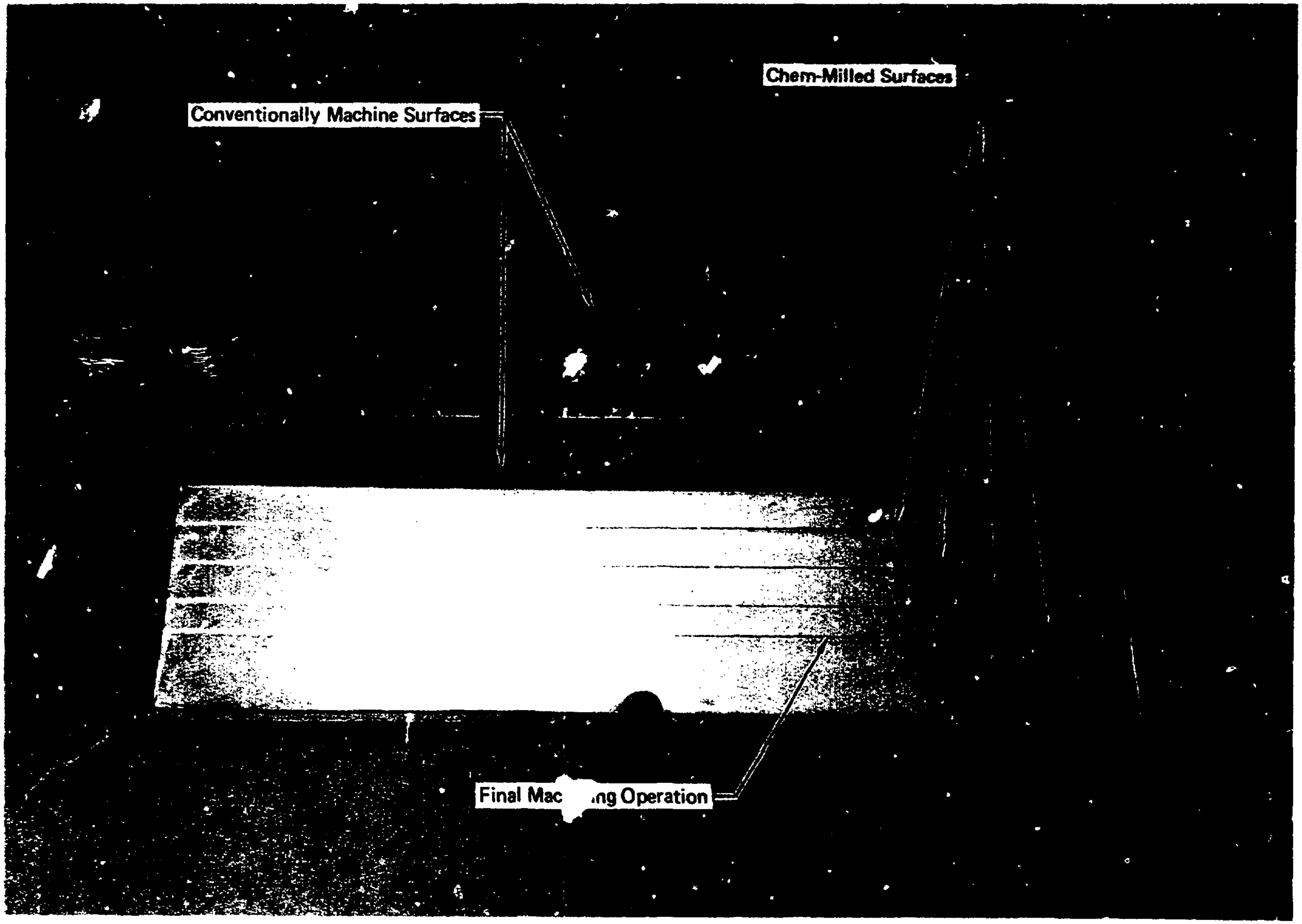


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FIGURE 38 TITANIUM SPLICE PLATE PRIOR TO FINAL MACHINING OPERATION

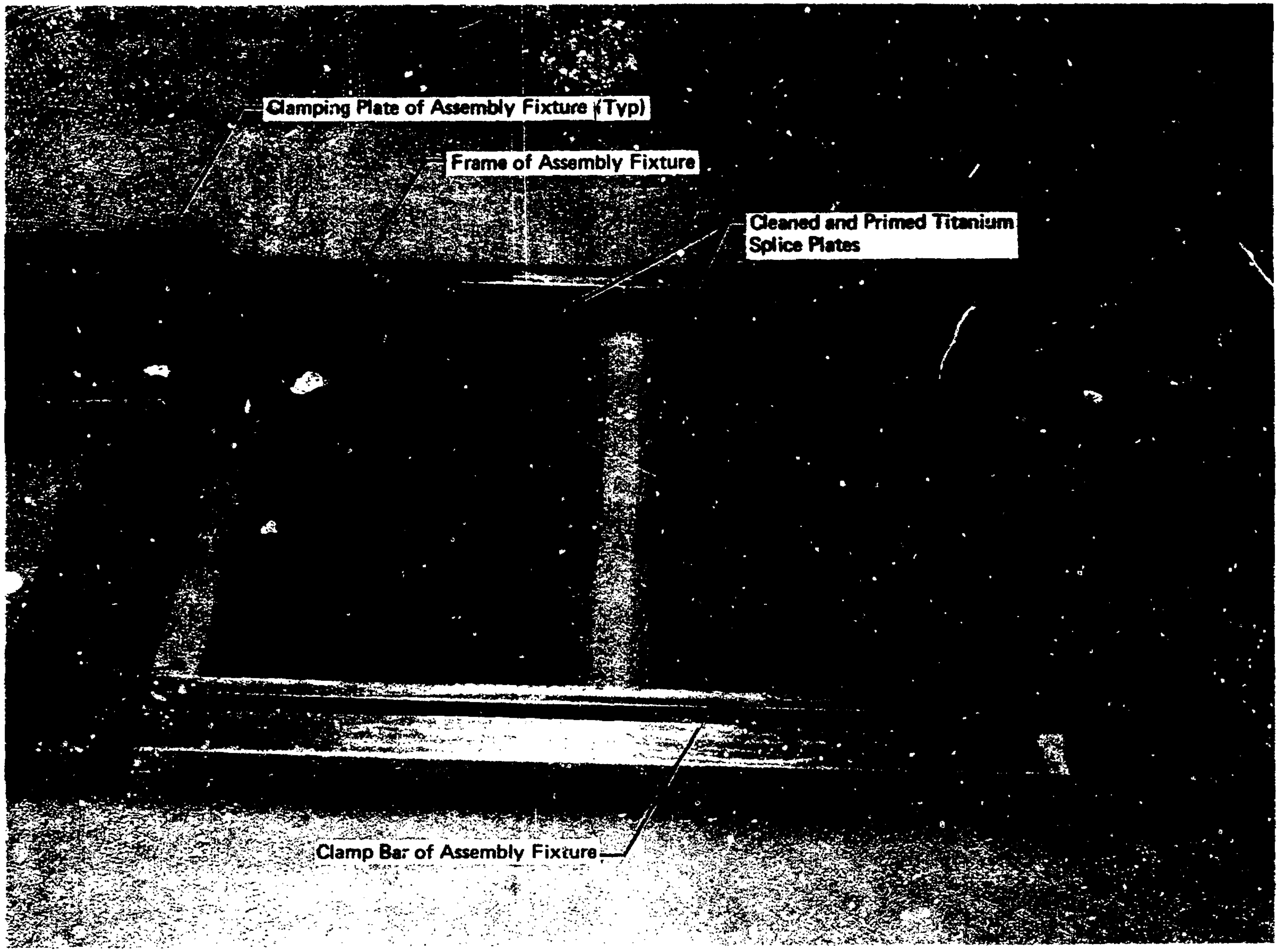

FIGURE 39 TITANIUM SPLICE PLATES POSITIONED IN ASSEMBLY FIXTURE

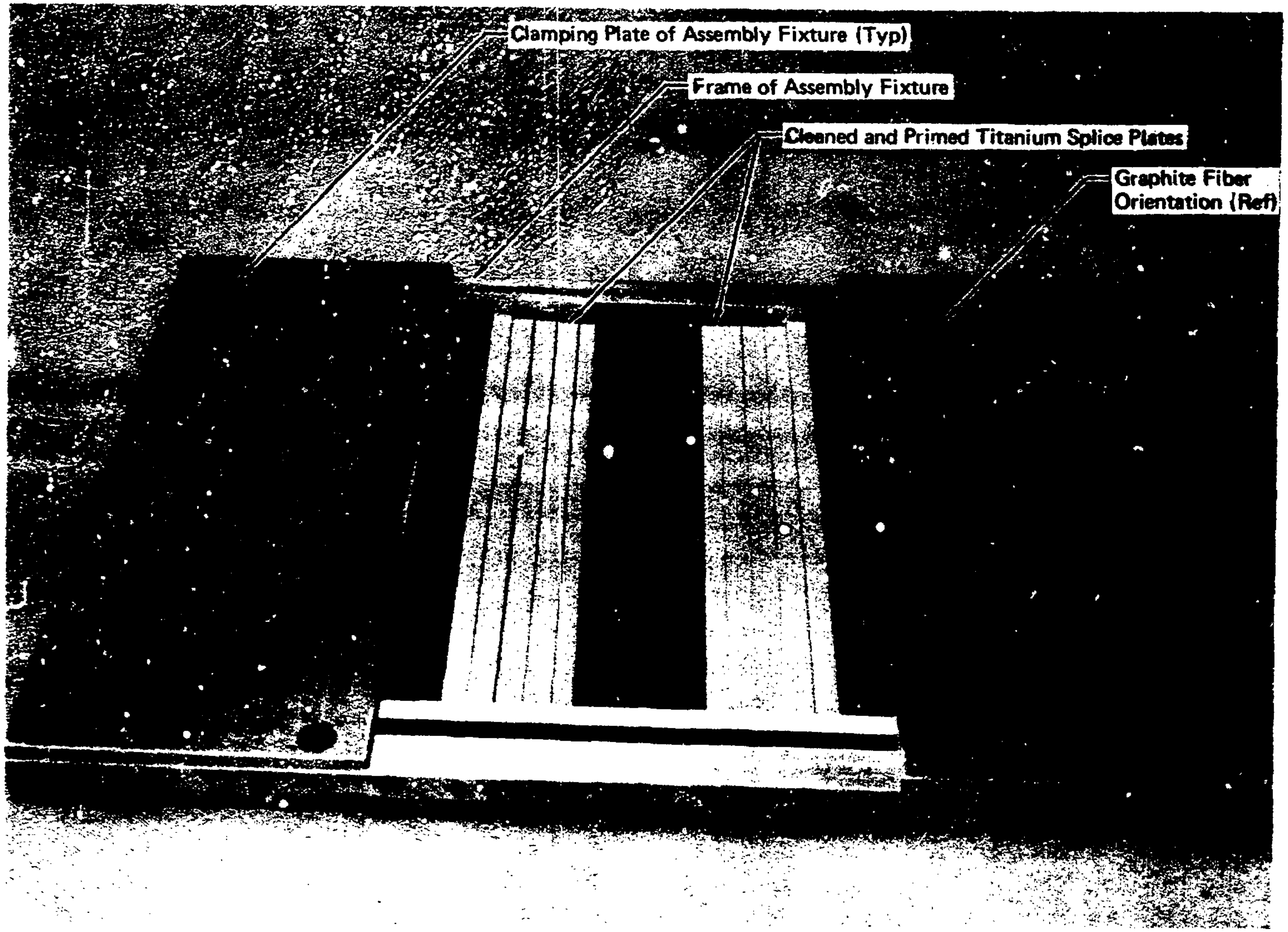

FIGURE 40 TITANIUM SPLICE PLATES AND ASSEMBLY FIXTURE CONFIGURATION BEFORE APPLYING THE MMS-307 TYPE I FILM ADHESIVE

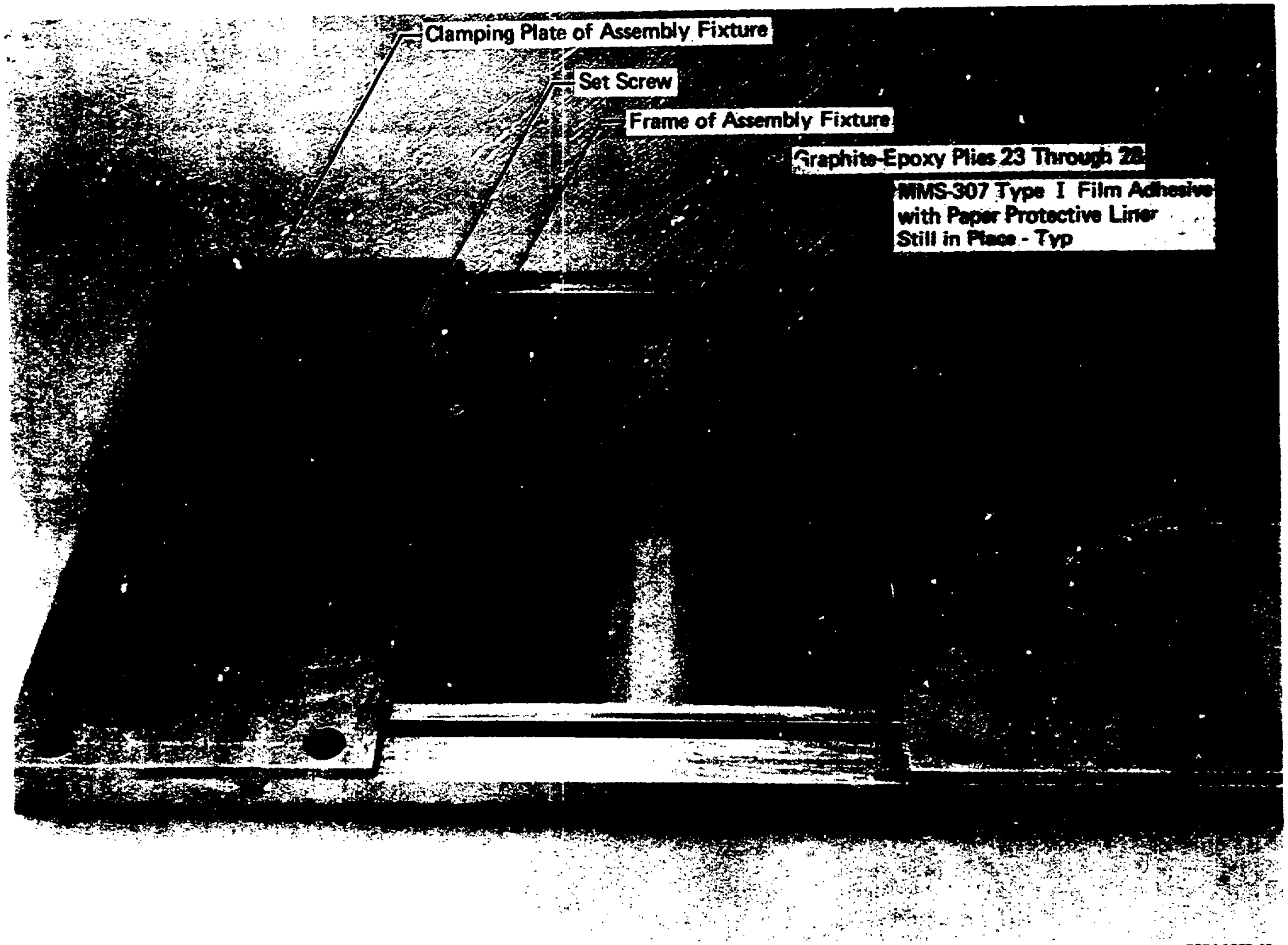

FIGURE 41 PANEL ASSEMBLY WITH GRAPHITE-EPOXY PLIES 23 THROUGH 28 AND MMS-307 TYPE I FILM ADHESIVE IN PLACE

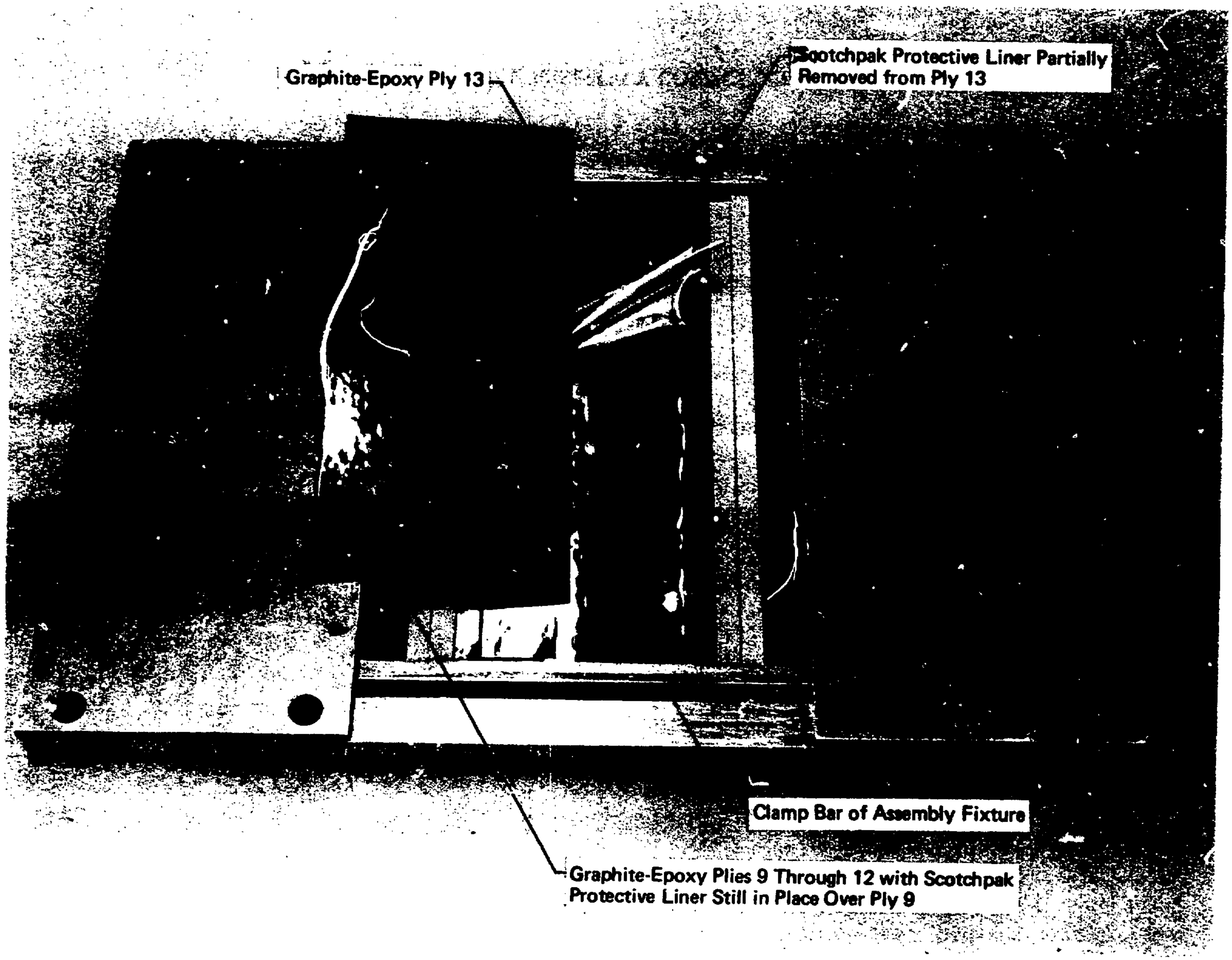

FIGURE 42 PANEL ASSEMBLY SHOWING PARTIALLY LAID UP GRAPHITE-EPOXY LAMINATE

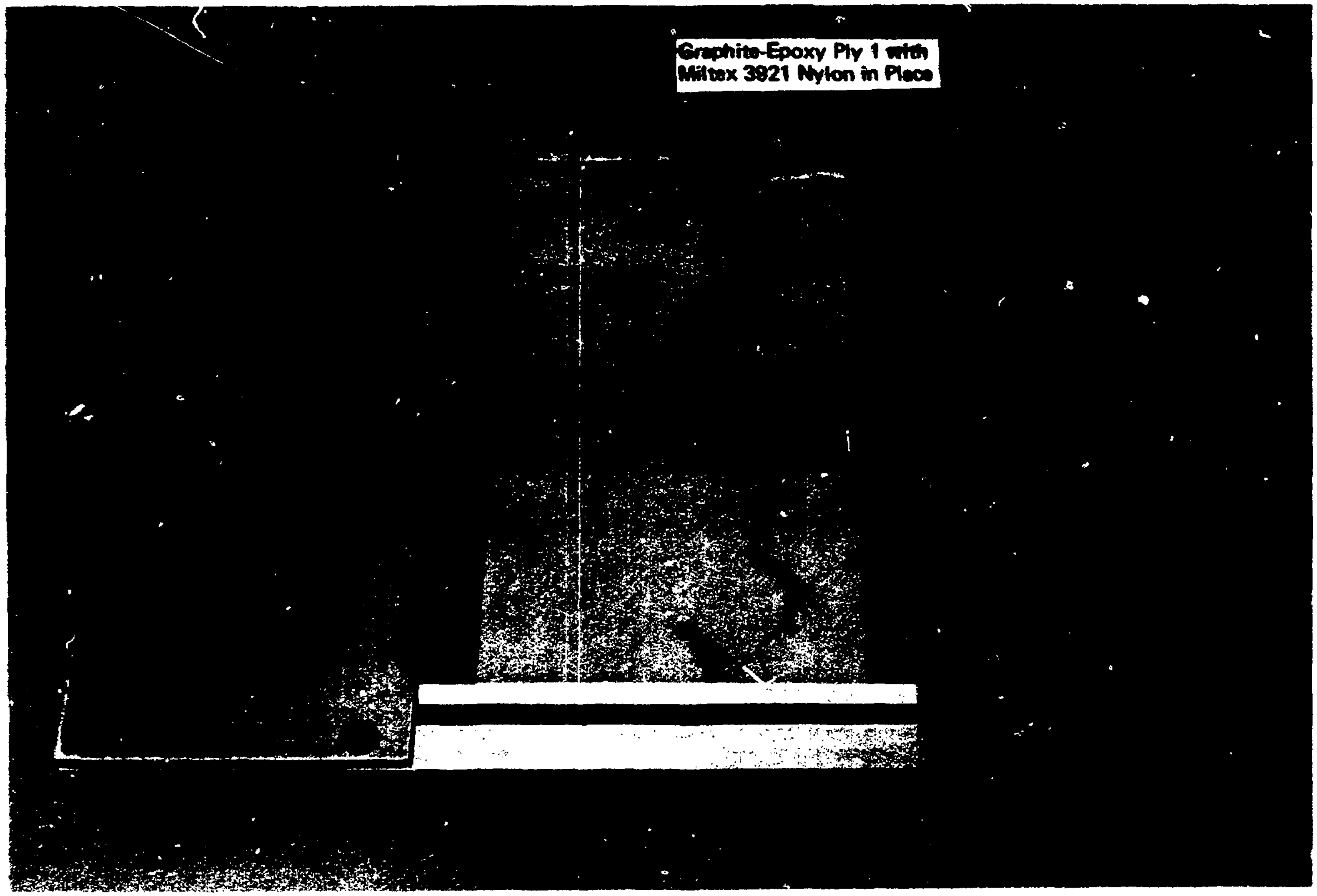

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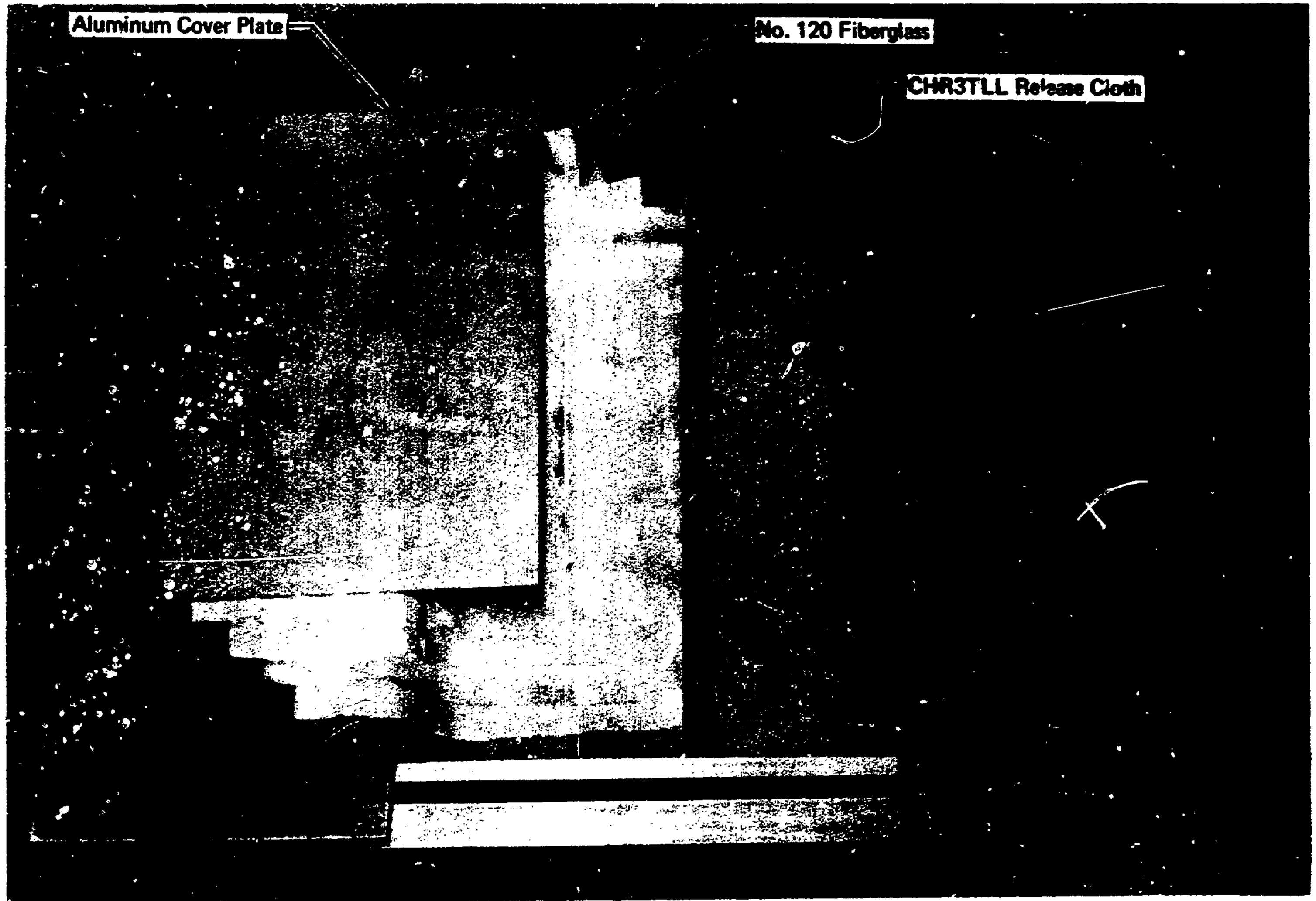
FIGURE 43 PANEL ASSEMBLY COMPLETELY LAID UP



GP74-1037-46

FIGURE 44 PANEL ASSEMBLY SHOWING LAY-UP CONFIGURATION DETAILS PRIOR TO FINAL POSITIONING

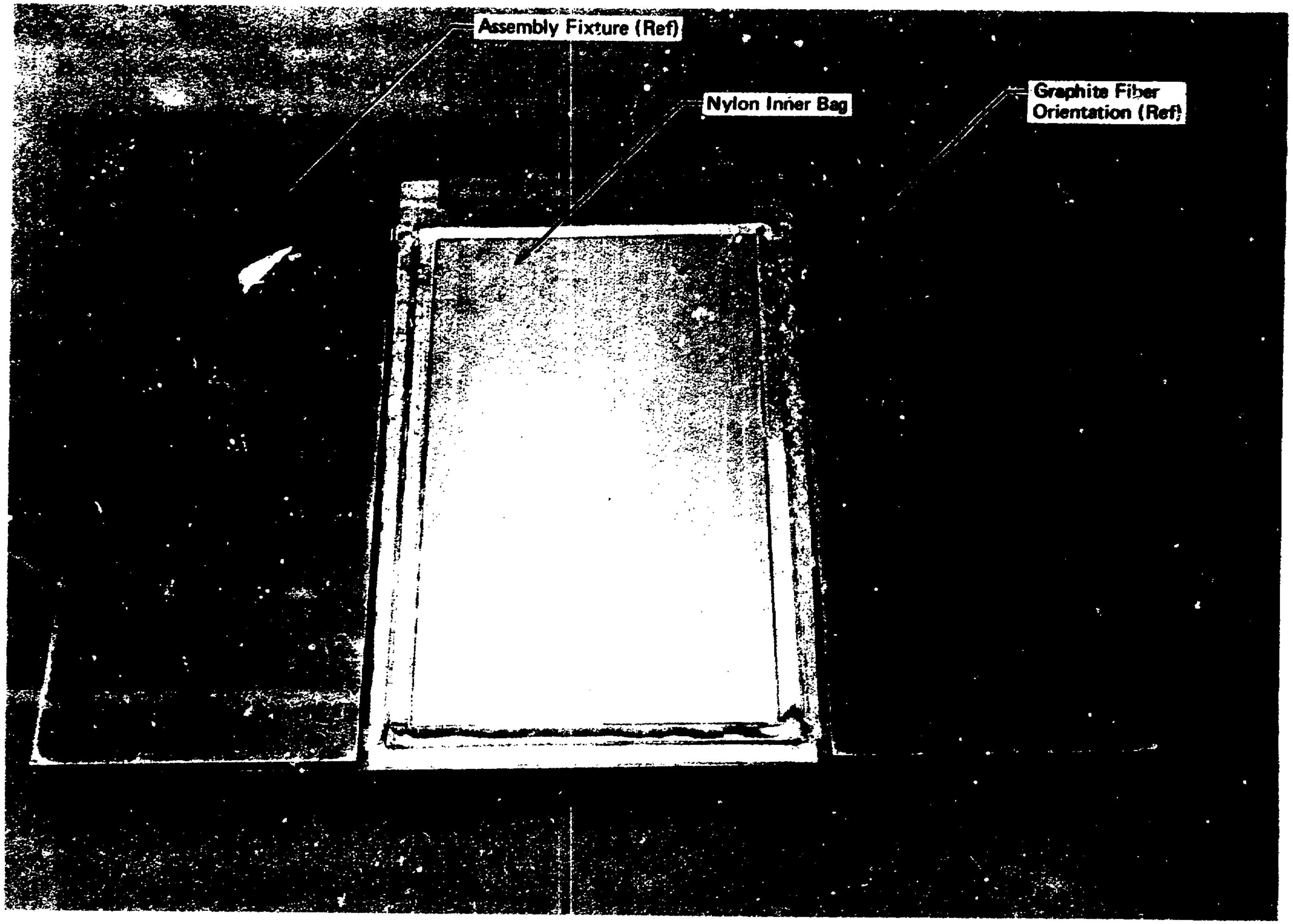


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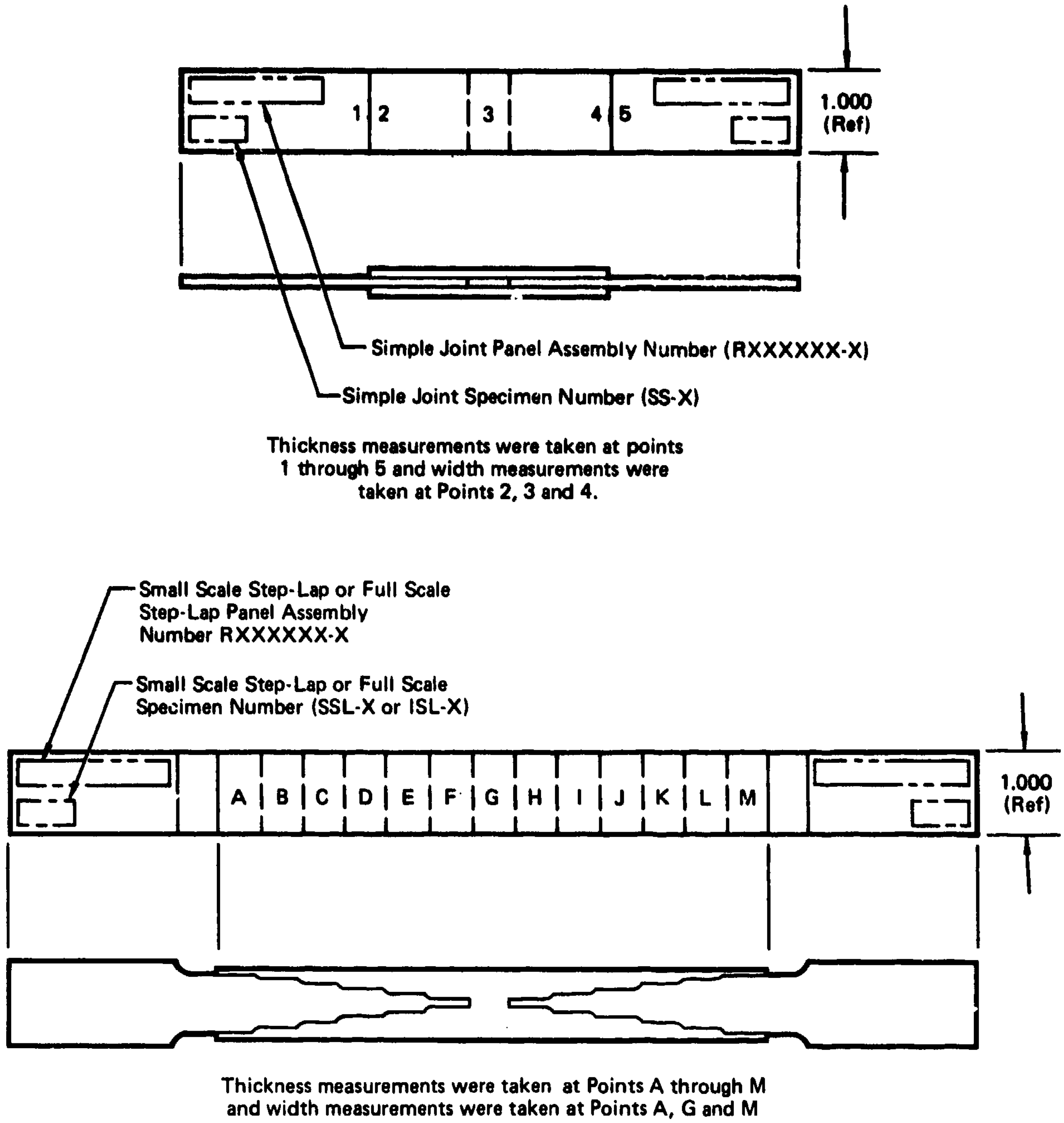
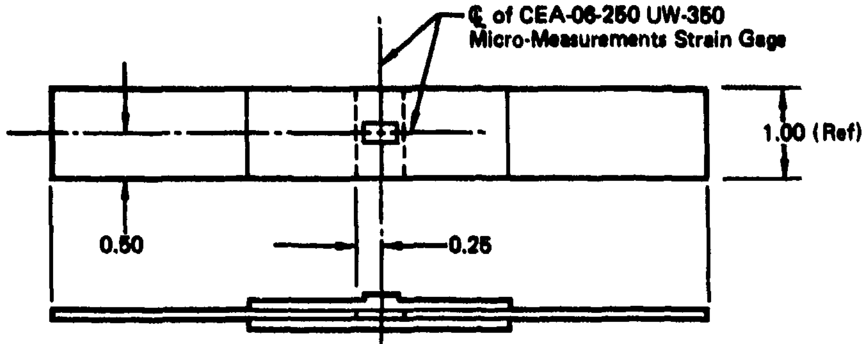
FIGURE 45 LAY-UP CONFIGURATION PRIOR TO BEING WRAPPED IN PINK RELEASE CLOTH AND NO. 1000 FIBERGLASS

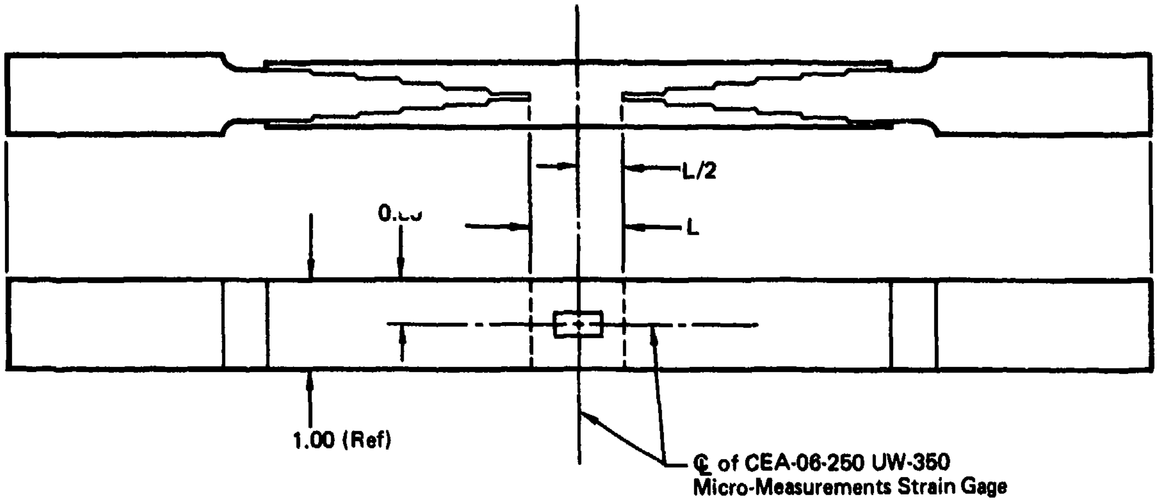


1037-30

FIGURE 46 THICKNESS AND WIDTH MEASUREMENT LOCATIONS



Location of Strain Gage on the Simple Joint Test Specimens



Location of Strain Gage on the Small Scale Step-Lap and Full Scale Step-Lap Test Specimen

FIGURE 47 STRAIN GAGE REQUIREMENTS

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TABLE 8 AUTOCLAVE RUNS IN WHICH THE SPECIMENS WERE CURED

Run No.	Run Date	*Specimen Nos.
1	24 July 1974	SS 1-60
2	25 July 1974	SS 61-90
3	8 Oct 1974	SSL 1-20
4	11 Oct 1974	SSL 21-40
5	15 Oct 1974	SSL 41-60
6	17 Oct 1974	SSL 61-80 and 36A
7	22 Oct 1974	SSL 81-100
8	25 Oct 1974	FSL 1-20
9	5 Nov 1974	FSL 21-40
10	12 Nov 1974	FSL 41-60
11	15 Nov 1974	FSL 61-80
12	20 Nov 1974	FSL 81-90

SS - Simple Specimen
SSL - Small Scale Step-Lap Specimen
FSL - Full Scale Step-Lap Specimen

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3.3 Non-Destructive Testing (NDT)

Each specimen evaluated under this program was radiographically, ultrasonically and visually inspected to insure acceptable quality.

The procedures used in the conduct of these inspections are discussed in paragraph 3.3.1. The inspection standard passed by the specimens is summarized in Paragraph 3.3.2.

3.3.1 Inspection Procedures - The procedures used in the conduct of the radiographic and ultrasonic inspections are discussed below:

Radiographic - Low Kilovoltage/high contrast techniques were used in accordance with MCAIR P.S. 21206.3 "Radiographic Inspection of Honeycomb Assemblies and Composite Structures". The test parameters were as follows:

- Kilovoltage - The kilovoltage used in each test was determined from Figure 48. The graphite-epoxy thickness was not considered in determining the kilovoltage over the titanium steps.
- Milliamperes/Minute - These are adjusted to obtain a film density in the area of interest of 2.5 to 3.5 H and D density units.
- Cassettes - Blackened film with 0.01 inch thick lead back screen was used.
- Backing - 1/8 inch thick lead lying behind the cassette.
- Processing - Automatic.
- Focal Spot to Film Distance - 58 inches.
- X-ray Machine Type - Constant potential, beryllium window with 0.4 and 3.0 millimeter focal spots (some radiographs were made with each size focal spot).
- Interpretation - All interpretors are qualified to at least SNT-TC-1A level II.

Ultrasonic - The ultrasonic inspections were conducted in accordance with MCAIR P.S. 21211.4 "Ultrasonic Inspection of Honeycomb Assemblies and Composite Structures." The reflector plate technique illustrated in Figure 49 was used. The test parameters were as follows:

- Ultrasonic Scope - Automatic Industries UM 721 (or UM 771B) with 10B pulser-receiver.
- Search Unit - A 5 MHz, 3/4 inch diameter, 3 inch focal length, ceramic search unit was used on all the double lap specimens and small

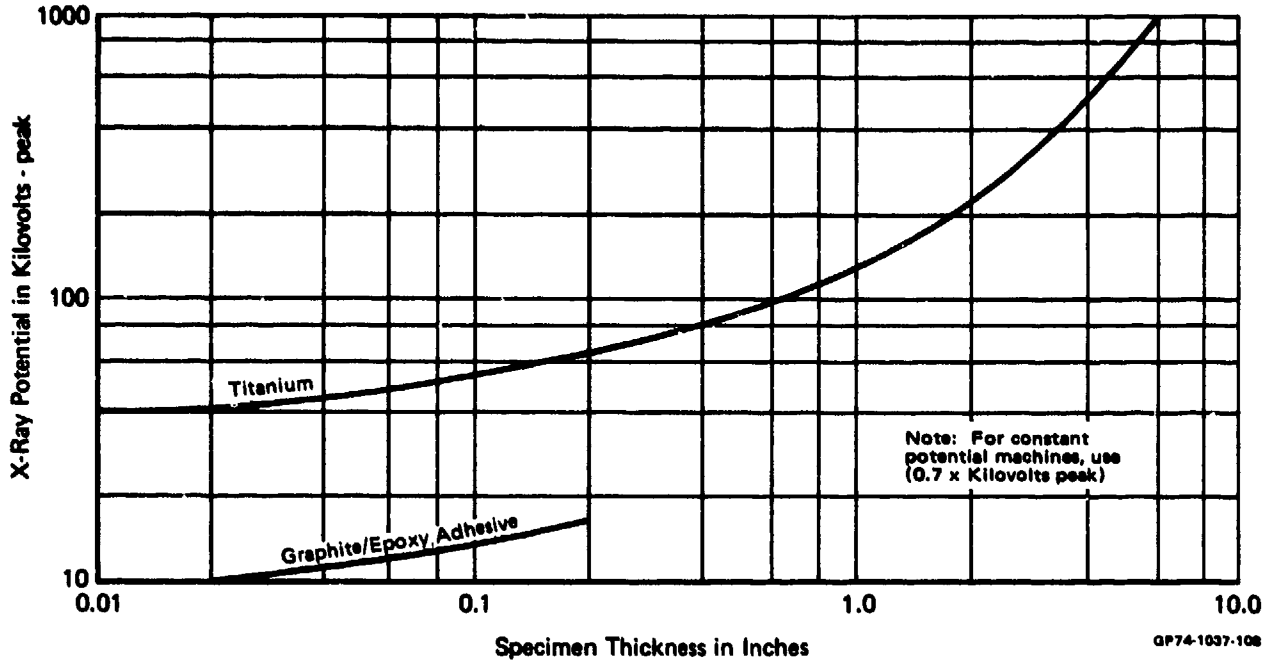


FIGURE 48 X-RAY POTENTIAL

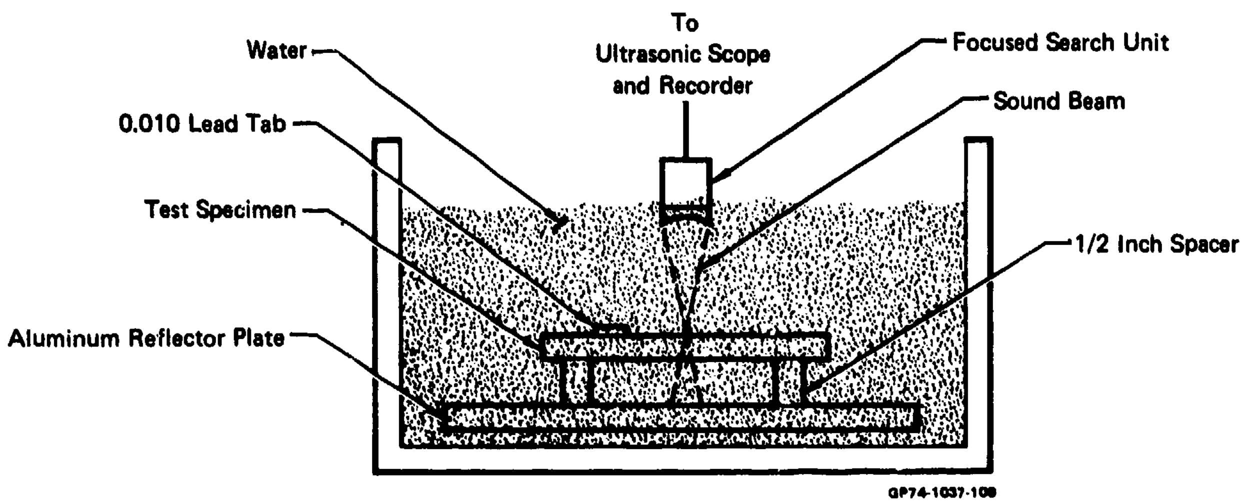


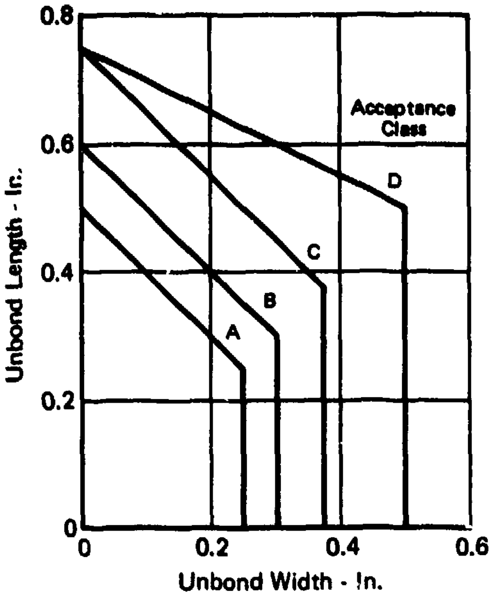
FIGURE 49 THE ULTRASONIC INSPECTION TECHNIQUE USED

scale step-lap specimens 1 through 40. In subsequent tests a 2.25 MHz, 3/4 inch diameter, 3 inch focal length, ceramic search unit was used.

- o Lead Tab - 1/4 inch diameter lead tabs, consisting of two .005 inch thick plies with adhesive backing, were used (one per step on each specimen) for calibration of the C-scan system.
- o Focusing - The search unit-to-test specimen distance was adjusted to focus round beam at sound entry surface.
- o Sensitivity - The instrument/recorder was adjusted until the print of the lead tab was actual size. Experience on other programs indicates that the minimum detectable void/unbond is about 1/8 inch in the minor direction.

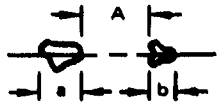
3.3.2 Specimen NDT Results - For this program a specimen was accepted if it passed the A acceptance class criteria identified in Figure 50. Ten of the full scale step-lap specimens (Numbers 44, 45, 46, 47, 51, 52, 53, 54, 58 and 59), which were laid up and cured with a total of twenty specimens on 12 November 1974, see Table 8, did not pass this criteria. These specimens had total disbond indications on the tang of one end. They would not have slipped by in a production NDT, since these specimens were being inspected by production NDT personnel and equipment. Tests were run on these specimens to verify NDT indications. As expected the strength of these specimens was inferior. This data was not used in the development of the wearout model.

These specimens are relatively narrow (one inch). For wide splice plates in representative aircraft structure a more liberal acceptance could undoubtedly be used. More effort needs to be expended in this area.



Notes:

1. W is the maximum projected unbonded width, measured across the void in the "narrow" direction. L is the projected unbonded length measured perpendicular to W.
2. The Engineering drawings, process specifications, or procurement specifications or documents shall specify the ratio (K) of the separation distance of any two voids to the dimension of the largest adjacent void where the dimension is measured along the line joining the two voids. This requirement is applicable to voids whose dimensions are smaller than the maximum allowable void for the particular class of acceptance but have minor dimensions in excess of 0.060 inches. For this program, K shall equal 4 for unbonds in the graphite to titanium joints and 8 for delaminations in the graphite/epoxy laminates.



A = K(a) and (a>b)

3. Parts with any voids having a minor dimension in excess of 0.060 inch and exceeding the maximum dimensions illustrated in the figure above for the applicable class are rejectable.

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FIGURE 50 DEFINITION OF ACCEPTANCE CLASSES FOR UNBONDS

SECTION 4

RANDOM SPECTRUM DEVELOPMENT

4.1 Mission Segment Cumulative Peak Load Factor Exceedance Curves

The F-15 air superiority fighter was designed for a 4000 hour lifetime with a scatter factor of four. The planned operational usage included a specific set of missions each with its own requirements. In particular, there were four different air-to-air missions, two different air-to-ground missions, and one instrumentation and navigation training type of flight. Each of these missions was further divided into mission segments, viz. ascent, cruise, combat, descent, and loiter. The speed, altitude, and gross weight were determined for each of these segments based on optimizing the airplane performance, mission range, fuel consumption, etc. Varying external loading distributions were used for each flight condition (defined by speed, altitude, gross weight and airplane configuration) where both symmetric and asymmetric maneuvers were executed based on the mission analysis. These external loading distributions were used in combination with the cumulative peak load factor exceedance curves to determine internal structure repeated loads for critical components. Ground loads were included as specified to apply the loads on a flight by flight basis.

A schematic of the cumulative peak load factor exceedance curves for the various F-15 mission segments is shown in Figure 51. These are given in terms of peak exceedances per hour of time spent in a given segment. For each of the seven basic F-15 missions, the time spent in each mission segment is determined by the mission analysis. These time lengths are multiplied times the appropriate curve in Figure 51 to obtain the total number of peaks for the mission segments of each mission. It is apparent from Figure 51 that combat maneuvering is considerably more severe than any of the others as would be expected. In fact, when the actual number of peaks are compared for the F-15 lifetime, 87% of all peaks exceeding 2 g's and 99% of all peaks exceeding 4 g's are recorded in the combat segments.

4.2 Random Test Methodology

Cumulative load exceedance curves for the F-15 wing root bending moment fatigue spectrum have been approximated with random load level applications on a flight by flight basis. The random load wave shapes have been determined from actual aircraft maneuver time histories recorded during combat

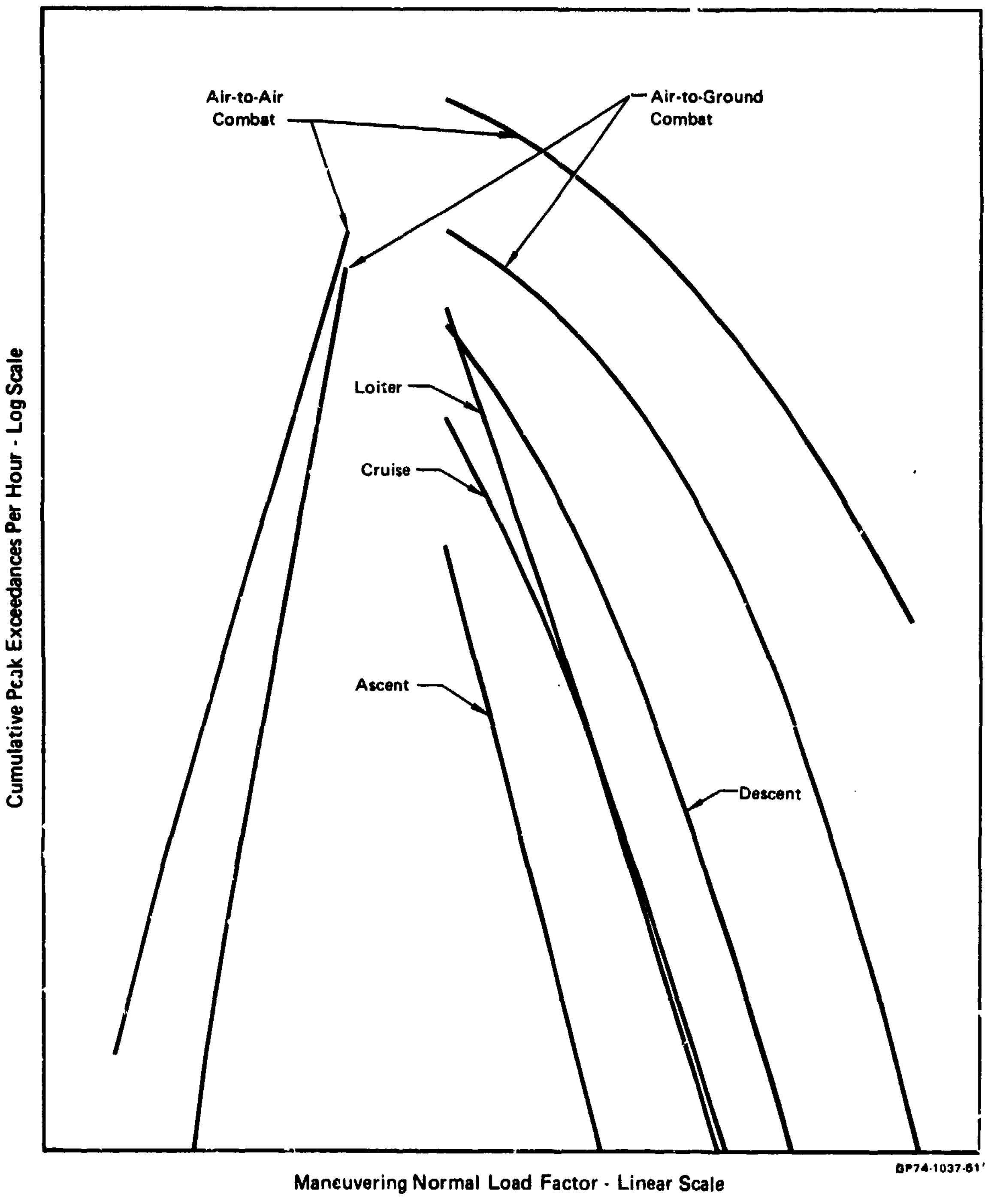

FIGURE 51 F-15 MISSION SEGMENT
Positive and Negative Peak Exceedance Curves - Maneuver Load Factor - N_Z

training. The detailed technical approach for matching the cumulative load exceedance curves and aircraft maneuver wave shapes using random noise theory is described in this section. The discussion of random load fatigue test experience in paragraph 4.2.1 and the brief discussion of random noise theory in paragraph 4.2.2 are included here to provide the necessary background for the detailed development of the flight by flight random fatigue spectrum given in paragraphs 4.2.3 through 4.2.5.

4.2.1 <u>Random Load Fatigue Experience</u> - In order to minimize testing complexity, the sequence of load level application for aircraft structural fatigue tests has oftentimes been very ordered, e.g., Lo-Hi or Hi-Lo, and in a specified block size. The effects of sequence, block size, negative loads, etc., have therefore become the subject of many fatigue test programs. References 12, 13, and 14 are but a few examples where the fatigue life was shown to vary by as much as an order of magnitude resulting from a sequence change usually associated with a high positive or high negative load level. MCAIR has conducted literally thousands of spectrum fatigue tests in conjunction with the F-101, F-4, and F-15 structural development programs. The significant effect of load level sequence and positive and negative loads was apparent in many of these tests. Typical results on aluminum and titanium are presented in Tables 9 and 10. Although these particular tests show that the random sequence of load levels gives more life than the Lo-Hi sequence, this trend is spectrum dependent. A variation in the fatigue spectrum shape could result in a random sequence producing the lower life. A method of life prediction developed at MCAIR, which shows favorable comparisons with the test results in Tables 9 and 10, is a cumulative damage analysis technique which accounts for the stress-strain variations at the specimen notch root critical location caused by local plasticity. These inelastic effects, which contribute toward the importance of load sequence, are taken into account using Neuber's rule and the cyclic stress-strain characteristics of the material in question. Development and application of this method is discussed in References 15 and 16.

Test results discussed in the preceding paragraph are all for metal specimens, but it is expected that bonded joints would also be significantly influenced by load level sequence effects. A review of aircraft load usage time histories indicates much more of a random sequence than any kind of an

TABLE 9 COMPARISON OF PREDICTED LIFE TO ALUMINUM FATIGUE TEST RESULTS FOR SPECIMENS WITH OPEN HOLES

Spectrum Definition		Test Life Laboratory Spectrum Hours	Life Predictions	
			Conventional n/N Computations	MCAIR Method
Spectrum A	Random Sequence Without Unloading	4300	4300	4300
	Random Sequence With Unloading	3040	4300	3070
	Random Sequence With Negative Loads	1750	3920	2050
	Lo-Hi Sequence With Unloading	2700	4300	2700
	Lo-Hi Sequence With Unloading Truncated at 85%	1510	4530	1650
Spectrum B	Lo-Hi Sequence With 1G Minimum	1420	1680	1150
	Lo-Hi Sequence With −1G Minimum	680	1500	625
	Lo-Hi Sequence With −3G Minimum	380	1300	450

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TABLE 10 COMPARISON OF PREDICTED LIFE TO TITANIUM FATIGUE TEST RESULTS FOR SPECIMENS WITH OPEN HOLES

Spectrum Definition		Test Life Laboratory Spectrum Hours	Life Predictions	
			Conventional n/N Computations	MCAIR Method
Spectrum C	Random Sequence of peaks 250 hour block size. Highest load = 131.6%	94,750	94,750	94,750
	Random Sequence of Peaks 250 Hour Block Size. Highest Load = 111.8%	55,250	94,750	62,000
	Lo-Hi Sequence of Peaks 250 Hour Block Size. Highest Load = 131.6%	24,250	94,750	18,000

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orderly application. This fact is primarily what has led to random load fatigue testing in the aircraft industry. The initial step in this direction for aircraft maneuver loads was reported by Payne in Reference 17 in 1956. Analysis of aircraft maneuver loading using random noise theory was first reported in the late 1950's by Mayer and Hamer (Reference 18). Analysis of aircraft gust loading using random noise theory was initiated in an earlier time frame. Clementson and Miles, References 19 and 20, respectively, published reports on the subject in the early 1950's. Both of these papers were based on mathematical analyses of random noise developed by Rice on 1945 and presented in Reference 21. Fatigue testing using electromechanical shakers driven by a Gaussian white noise generator was the obvious next step. References 22 through 25 describe typical laboratory studies in this area spanning the time period from 1959 to 1972. These tests simulated aircraft gust loading environment. MCAIR has developed techniques for the F-15 using servohydraulic test equipment to simulate aircraft maneuver loading environment on a flight by flight basis with ground loads applied between each flight. These techniques represent the basis of the fatigue test approach used in this program. The selection of the wave form shape is based on actual fighter aircraft flight time histories of air-to-air combat maneuvering and air-to-ground combat maneuvering.

4.2.2 Random Noise Theory - If it is assumed that the load x(t) on a given structural element is a stationary random function of time, the probability density function of x(t) is independent of time and defined as the probability that x(t) will fall within the range of x to x + dx at any instant in time. If this probability density function takes on the classical Gaussian or normal form, (it should be emphasized that many random processes approach this function by virtue of the powerful central limit theorem) the time history appearance of x(t) would be anywhere between the two wave shapes shown in Figure 52. The wave shape is governed by the frequency distribution of x(t). The wave shape called narrow band in Figure 53 obviously consists of variable amplitude cycles of very nearly the same frequency. The term narrow band refers to the limited frequency bandwidth existing in the time history of x(t). Similarly, the wave shape called wide band in Figure 53 also consists of variable amplitude cycles, but with a significant spread in the cyclic frequency. The term wide band refers to the generally unlimited frequency bandwidth existing in the time history of x(t).

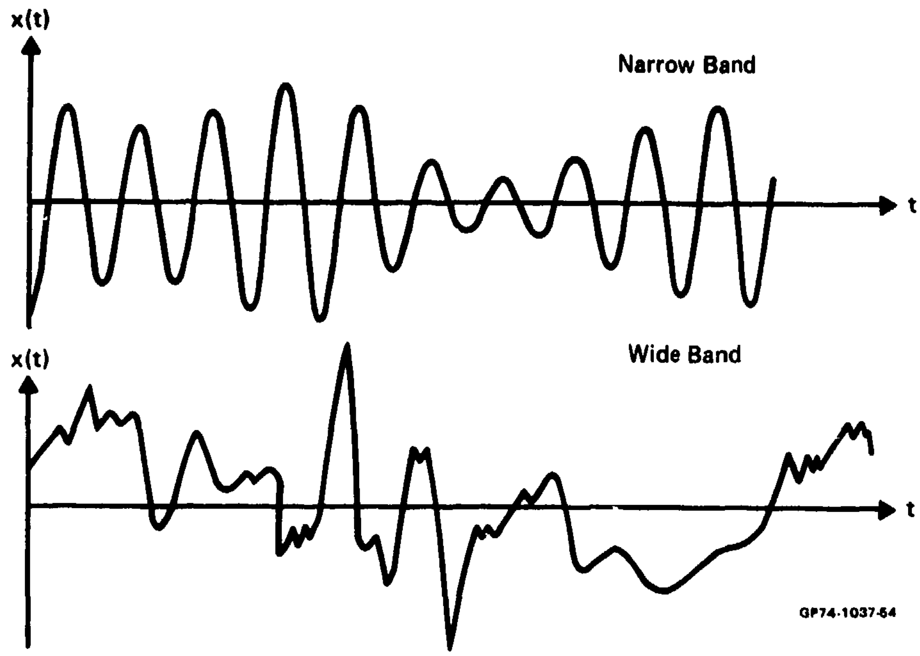


FIGURE 52 TIME HISTORY WAVE SHAPES FOR GAUSSIAN RANDOM NOISE

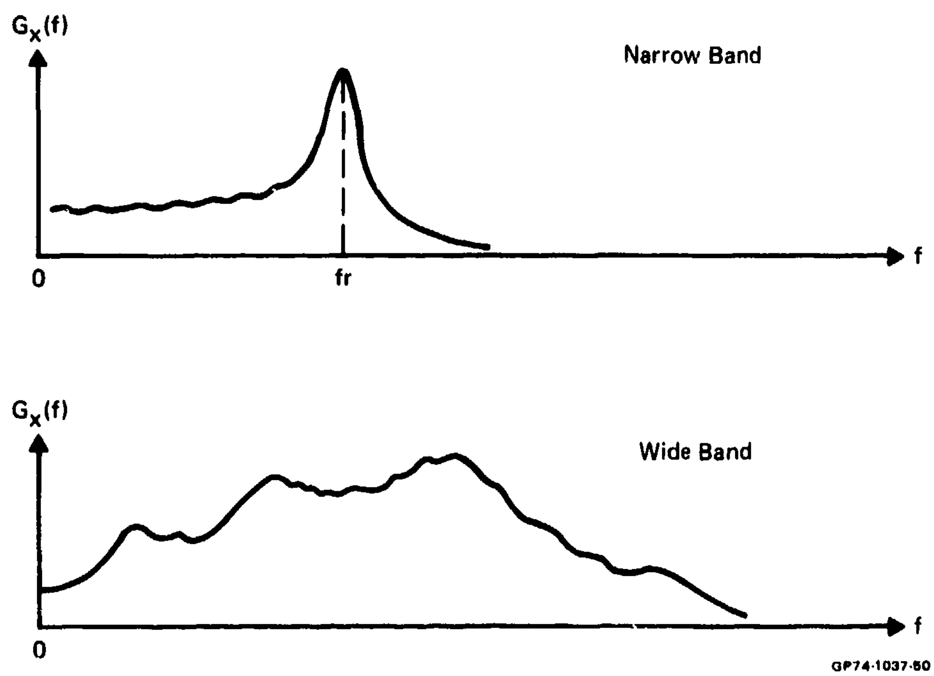


FIGURE 53 POWER SPECTRAL DENSITY vs FREQUENCY

The frequency distribution of $x(t)$ which governs its wave shape is specified by $G(f)$, the power spectral density of $x(t)$. It quantitatively defines the density of the mean square value of $x(t)$ at any given frequency. The integration of this density, therefore, over the entire range of frequencies yields the mean square of $x(t)$. The power spectral densities for the time histories in Figure 52 are presented in Figure 53. The mean square value of $x(t)$ is given by the area under the Figure 53 curve. The square root of this area is the root mean square (RMS) value for $x(t)$. The mean square value of $x(t)$ is specifically called the autocorrelation function $R(\tau)$ at $\tau = 0$. The autocorrelation function is determined from $x(t)$ as follows:

$$R(\tau) = \underset{T \to \infty}{\text{Limit}} \frac{1}{T} \int_{o}^{T} x(t)\ x\ (t + \tau)\ dt \tag{6}$$

As indicated earlier the equation above for $R(\tau)$ evaluated at $\tau = 0$ gives the mean square value of $x(t)$. The autocorrelation function and the power spectral density are related by the Fourier inversion formulae:

$$G(f) = 4 \int_{o}^{\infty} R(\tau) \cos 2\pi f\tau d\tau \tag{7}$$

$$R(\tau) = \int_{o}^{\infty} G(f) \cos 2\pi f\tau df \tag{8}$$

It is of interest to note that if τ is set equal to zero in the second equation above, it reduces to the integration of the power spectral density over the entire range of frequencies which then equals the autocorrelation function at $\tau = 0$ or the mean square value of $x(t)$ as stated above.

If the probability distribution of $x(t)$ is Gaussian, the probability distribution of the maxima or peaks of $x(t)$ will either be Gaussian, Rayleigh, or somewhere in between depending on the power spectral density of $x(t)$. In particular for a narrow band process, the probability density of the peaks of $x(t)$ is Rayleigh. For a wide band process, the probability density of the peaks is Gaussian. In terms of structural fatigue design criteria, the distribution of peaks is usually defined by cumulative peak exceedance curves. For a frequency distribution between the two extremes of narrow and wide band random noise, the cumulative peak exceedance N_x is given as follows:

$$N_x = N_p P(x/a\sigma) + N_o[1-P(x/b\sigma)]e^{-x^2/2\sigma^2} \tag{9}$$

where N_p = total number of peaks per unit time

N_o = total number of zero (or mean level) crossings per unit time with positive slope

$P(x/a\sigma)$ = probability of exceeding $x/a\sigma$ determined from a standard Gaussian or normal probability table

σ = root mean square (RMS) of $x(t)$

a = $\sqrt{1 - (N_o/N_p)^2}$

b = $a/(N_o/N_p)$

It is of interest to note the variation in N_x with the ratio N_o/N_p sometimes called the irregularity factor. For $N_o/N_p = 1$, $a = b = 0$ and therefore $P(x/a\sigma) = P(x/b\sigma) = 0$ which gives

$$N_x = N_p\, e^{-x^2/2\sigma^2} \tag{10}$$

which is the Rayleigh distribution. This should represent a narrow band process. Figure 52 demonstrates this fact since it is apparent that the number of peaks equals the number of zero crossings (with positive slope) for the narrow band time history. For $N_o/N_p = 0$, $a = 1$ and $b \to \infty$ and therefore $P(x/b\sigma) = 1$ which gives

$$N_x = N_p\, P(x/\sigma) \tag{11}$$

which is the Gaussian distribution. This should represent a broad band process. Figure 52 also demonstrates this fact since it is apparent that the number of peaks is much greater than the number of zero crossings (with positive slope) for the broad band time history. The calculation of N_o/N_p is based on the following equations:

$$N_o^2 = \frac{\int_o^\infty f^2\, G(f)\, df}{\int_o^\infty G(f)\, df} \tag{12}$$

$$N_p^2 = \frac{\int_o^\infty f^4\, G(f)\, df}{\int_o^\infty f^2\, G(f)\, df} \tag{13}$$

4.2.3 Load Time History Wave Shape - The frequency distribution which governs the load time history wave shape is specified by the curve of power spectral density (PSD) versus frequency. In order to determine appropriate PSD versus frequency curves for fighter aircraft, actual load factor time histories from F-4's were analyzed. A total of 5,658 seconds of air combat maneuvering training data and 15,675 seconds of air to ground combat maneuvering training data were included in the calculations. These data were digitized and then numerical techniques used to perform the integration specified in Figure 54 where $x(t)$ represents a typical load factor time history. The resulting PSD versus frequency curves for air to air maneuvering and air to ground maneuvering are shown in Figure 55 and 56 , respectively. A side by side comparison of an actual load factor time history during air combat maneuvering and a Gaussian random noise time history with the air to air PSD is presented in Figure 57 . The one to one likeness of the two charts is considered to represent the primary justification for utilizing this approach in fatigue testing.

4.2.4 Cumulative Peak Exceedances - Press, et al. in Reference 26 presents a method of fitting measured gust peak distribution curves with combinations of Rayleigh distributions with different RMS values. Their method is based on an approximation of the peak distribution by the level crossing distribution which is always Rayleigh as shown by Rice in Reference 21 for a Gaussian random process. This same approximation is made by Manning, et al, in Reference (8). However, this approximation using the Rayleigh is

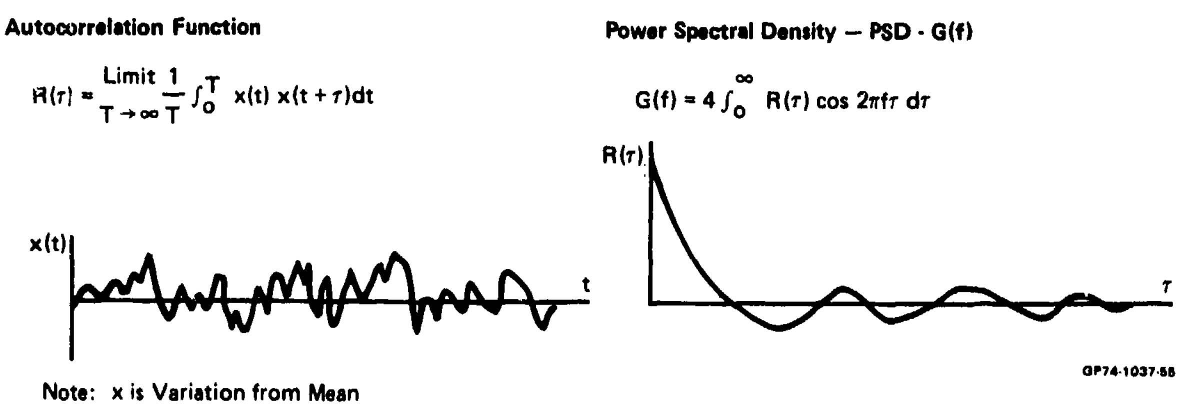


FIGURE 54 COMPUTATIONS FOR PSD

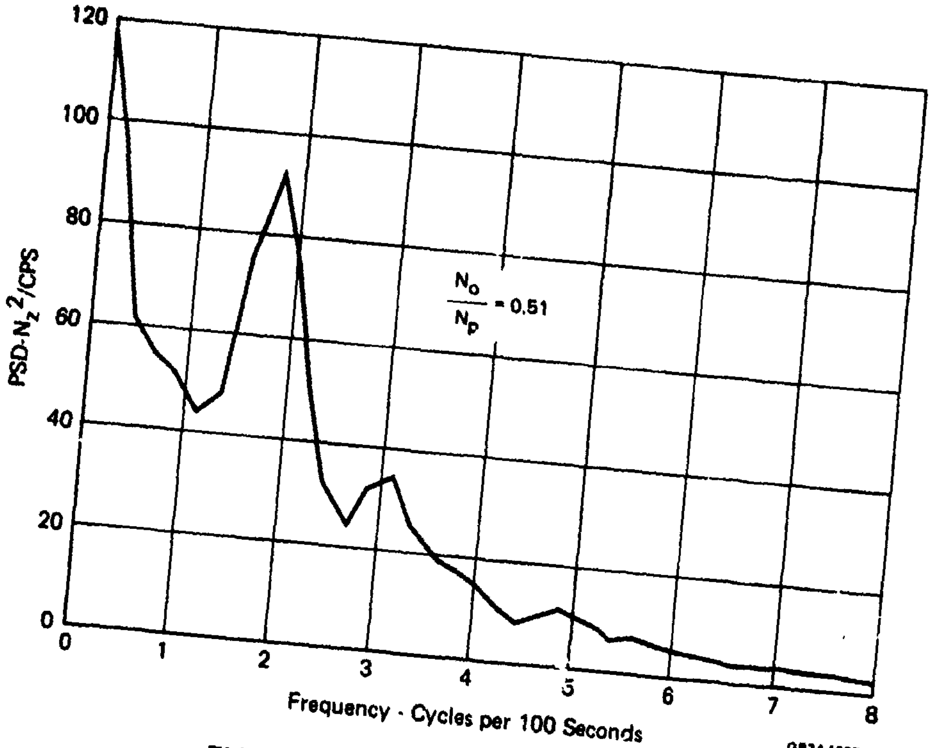


FIGURE 55 PSD vs FREQUENCY
Air-To-Air Training Data - 5658 Seconds

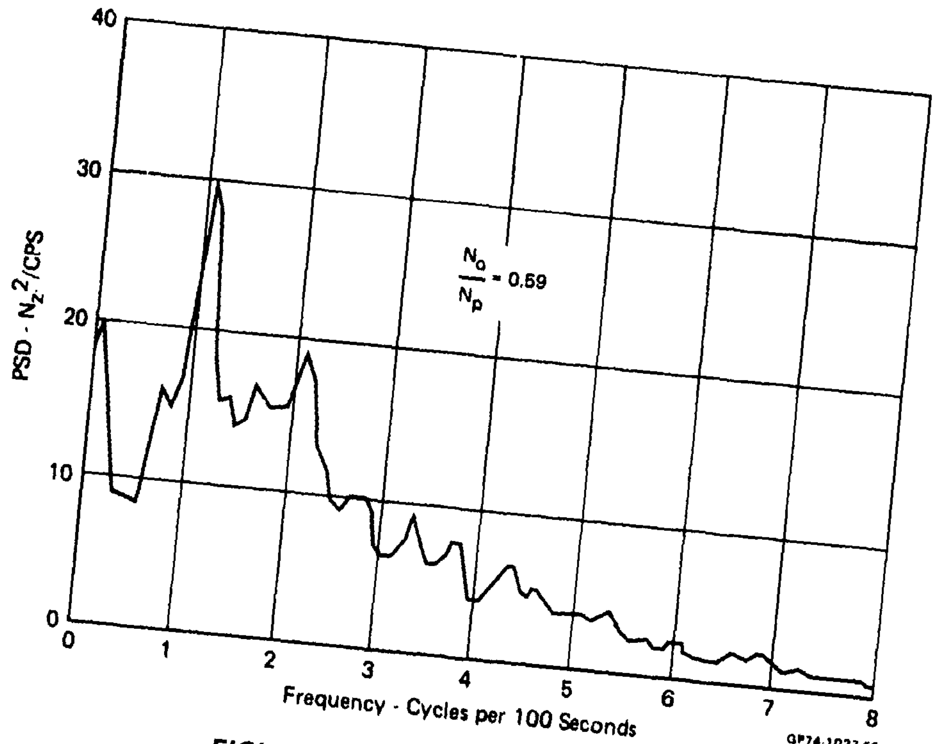
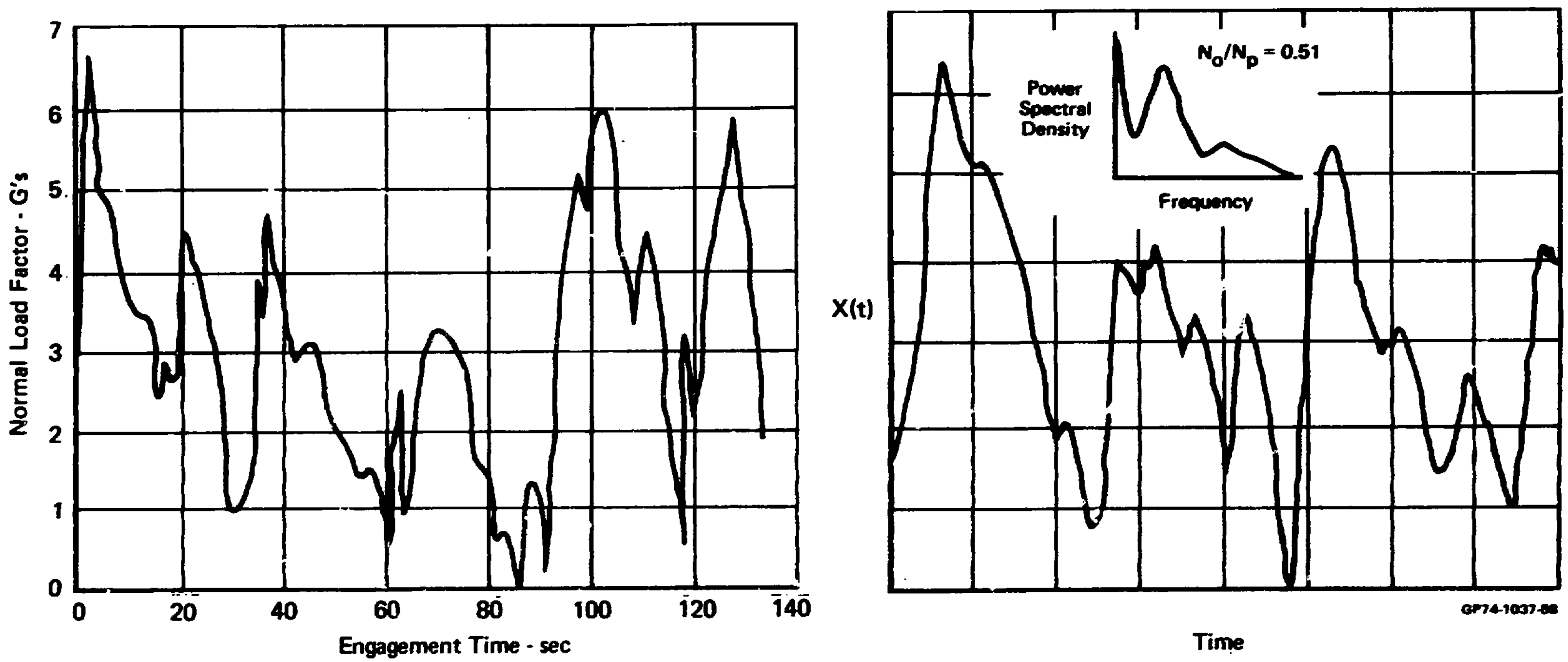


FIGURE 56 PSD vs FREQUENCY
Air-To-Ground Training Data - 15,675 Seconds



High Performance Fighter Aircraft
Air Combat Maneuvering

Gaussian Random Time History
For Air-to-Air PSD

FIGURE 57 COMPARISON OF ACTUAL LOAD FACTOR TIME HISTORY WITH A GAUSSIAN RANDOM NOISE TIME HISTORY

considered unnecessary since the exact distribution of peaks is readily determined as discussed in the following paragraphs.

Rice derived the exact probability density function for peaks and presented it as Equation 3.6-5 in Reference 21. The equation appears rather unwieldly but in fact is relatively straightforward. Huston and Skopinski in Reference 27 modified the terms, somewhat simplifying the appearance of the equation, and integrated it to obtain the number of peaks per unit time exceeding any given value of x. The resulting expression is given by Equation 9 in Section 4.2.2. This equation became more widely publicized when it was presented in Reference 28 by Bendat, et.al., in 1961. Then in 1964, Bendat used the equation again in a discussion of peaks, fatigue damage, and catastrophic failures in Reference 29. The equation requires only simple computations utilizing a standard Gaussian probability table. It includes basically four constants, viz., the total number of peaks N_p, the irregularity factor N_o/N_p and the mean and RMS values for x(t). This provides reasonable flexibility to fit most aircraft cumulative peak exceedance curves, espeically when the random process can also be clipped at one end or the other or both and added to another random process with different mean and RMS values. A typical theoretical exceedance curve using the equation above is shown in Figure 58. Another exceedance curve using a smaller RMS value is shown in Figure 59 and the sum of the two is shown in Figure 60. The peak exceedance curves in Figures 58 through 60 define the number of times in the random load excursions that the peak of a cycle exceeds a given load level in the positive direction in 1000 spectrum hours. Similarly, the valley exceedance curves define the number of times in the random load excursions the valley or trough of a cycle exceeds a given load level in the negative direction in 1000 spectrum hours.

4.2.5 Flight by Flight Spectrum - The step by step procedures for the flight by flight random spectrum generation are as follows:

- o Continuous Gaussian random noise signal is generated using a specified PSD shape and RMS level.
- o The continuous time history is digitized and transcribed onto computer compatible magnetic tape.
- o A computer program is written to count the peaks and valleys to verify conformance with theoretically derived exceedance curves.
- o Incremental segments of the digitized time history are separated by digitally added ground cycles to form the flight by flight spectrum.

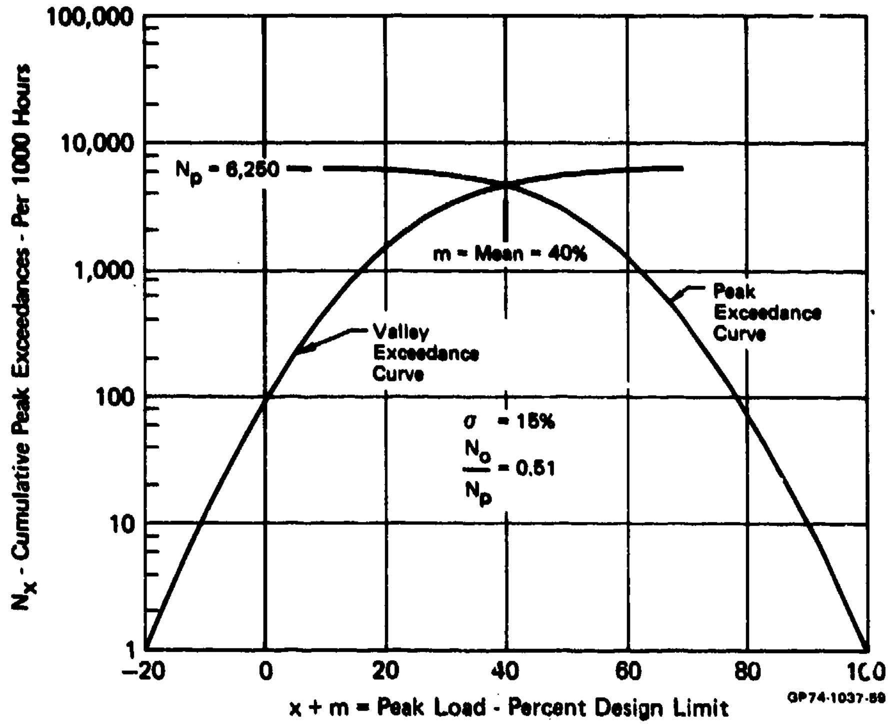


FIGURE 58 TYPICAL EXCEEDANCE CURVES

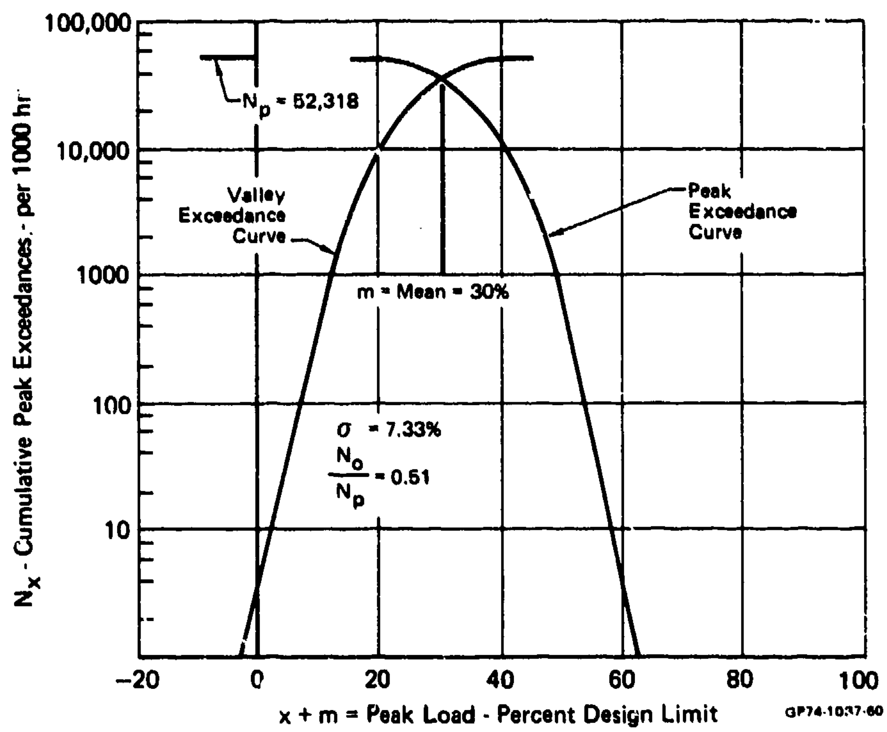


FIGURE 59 TYPICAL EXCEEDANCE CURVES (LOWER RMS)

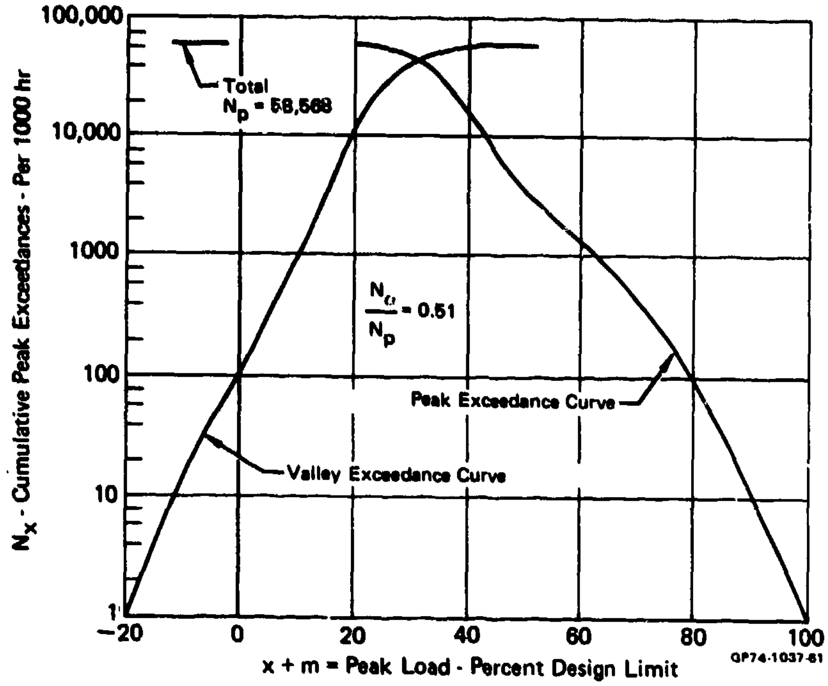


FIGURE 60 SUM OF TWO EXCEEDANCE CURVES

- A digital to analog subsystem converts the digitized flight by flight spectrum to a corresponding analog signal required for the fatigue test machine.

The spectrum includes a total of 720 flights or missions in 1000 hours. The detailed listing for the test sequence of the various F-15 missions is as follows:

25 missions of A-A1 followed by
52 missions of A-A2 followed by
77 missions of A-A3 followed by
28 missions of A-A4 followed by
177 missions of A-G followed by
25 missions of A-A1 followed by
52 missions of A-A2 followed by
78 missions of A-A3 followed by
28 missions of A-A4 followed by
178 missions of A-G

1000 hours of F-15 usage

It is expected that the F-15 operational usage will include deployment in particular modes of operation for extended periods of time rather than a completely erratic mission mixture. The above sequencing of missions wherein air-to-air missions are grouped together and air-to-ground missions are grouped together was selected on that basis. The four air-to-air missions are different with respect to fatigue loading primarily as a result of different lengths of time in the combat maneuvering segment. The A-A4 (air to air four) mission is more severe than A-A3 on a per mission basis; A-A3 is more severe than the A-A2; A-A2 is more severe than A-A1. The A-G (air-to-ground) mission is about equal in severity to A-A1. Each of the 720 missions in the 1000 hour sequence is in general different since each consists of a different sample of the governing random process. This complete 1000 hour record was analyzed; in particular, peaks and valleys were counted when there was at least an equivalent 1.00 g rise and 0.75 g fall or vice versa which represents the techniques used in developing the F-15 cumulative peak exceedance curves. In addition, the irregularity factor N_o/N_p for the complete 1000 hours was computed as were the power spectral density shapes. These computations provided satisfactory comparisons with the desired cumulative peak exceedance curves and time history wave shapes. The final 1000 hour tape was applied over and over again in the fatigue testing so that all specimens were subjected to exactly the same repeated loading history. Example time histories of the various missions and comparisons to the semi random spectrum used in the F-15 full scale fatigue test are presented in Figures 61, 62 and 63.

Two random spectra were developed to evaluate the effect of adding low load level cycles. The parameters used for these spectra are given in Figure 64. Random spectrum #2 is the same as #1 except an additional time burst of a lower RMS signal is added before and after the Random Spectrum #1 cycles in each mission. A comparison of the time histories of these two spectra is given in Figure 65. It should be emphasized that these added low load cycles would be expected to occur in the combat segments; the non-combat segments such as the cruise segment also have low load level cycles but only an insignificant number compared to combat. A third time history shows another variation to Random Spectrum #1 wherein hold time is added at zero load. A comparison of the peak exceedances per 1000 hours for Random Spectrum #1 and #2 is given in Figure 66. A comparison to the semi-random spectrum is also shown.

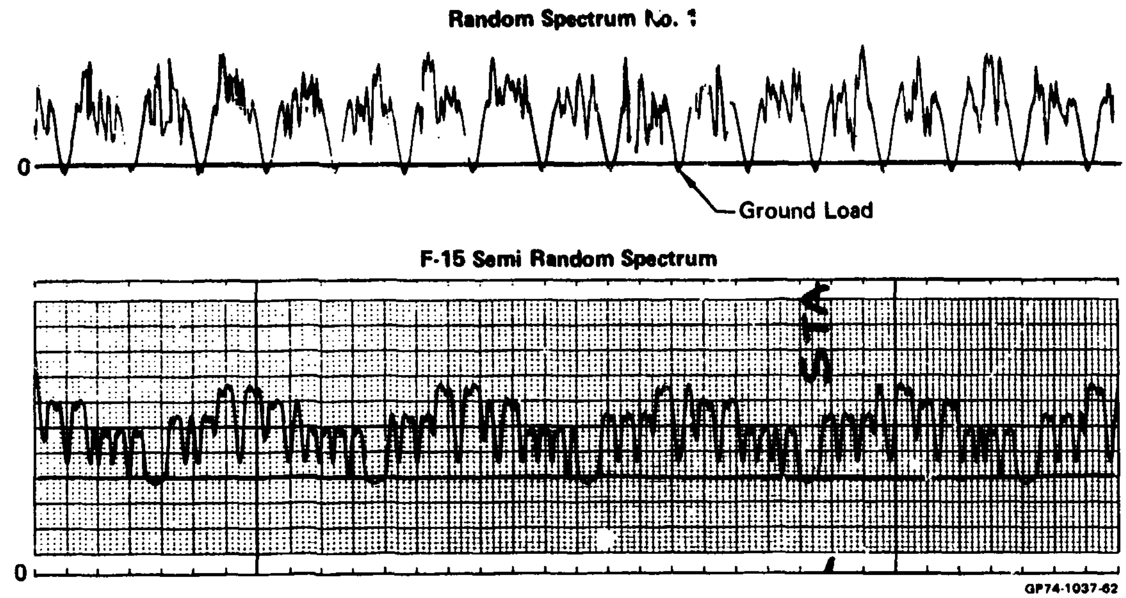


FIGURE 61 EXAMPLE TIME HISTORY OF A-A2 MISSIONS

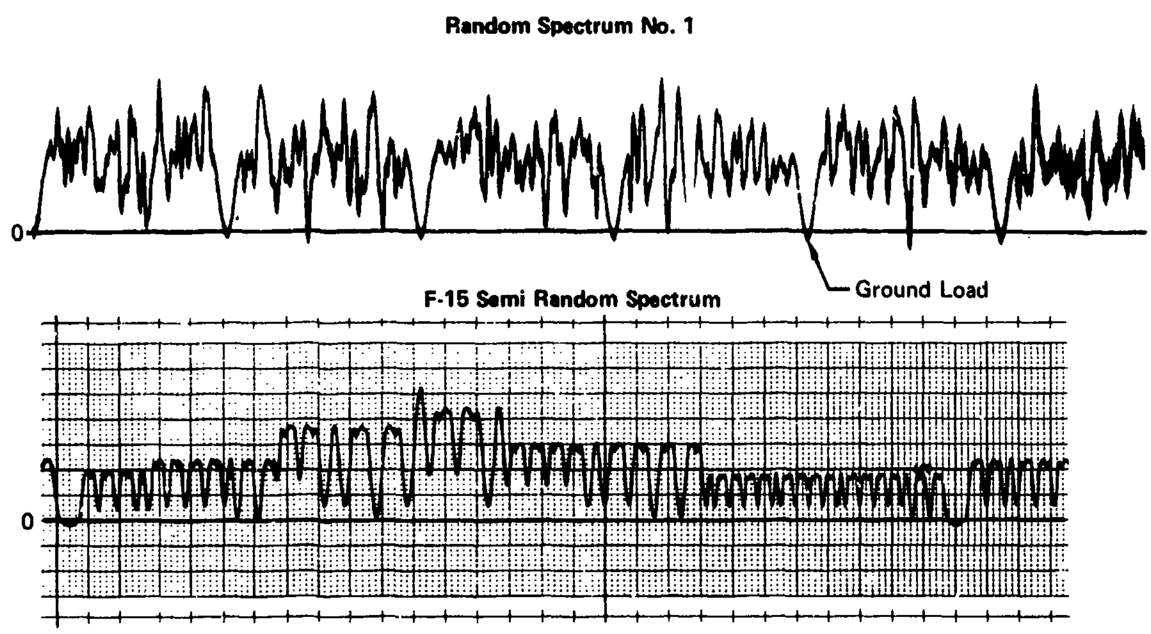


FIGURE 62 EXAMPLE TIME HISTORY OF A-A4 MISSIONS

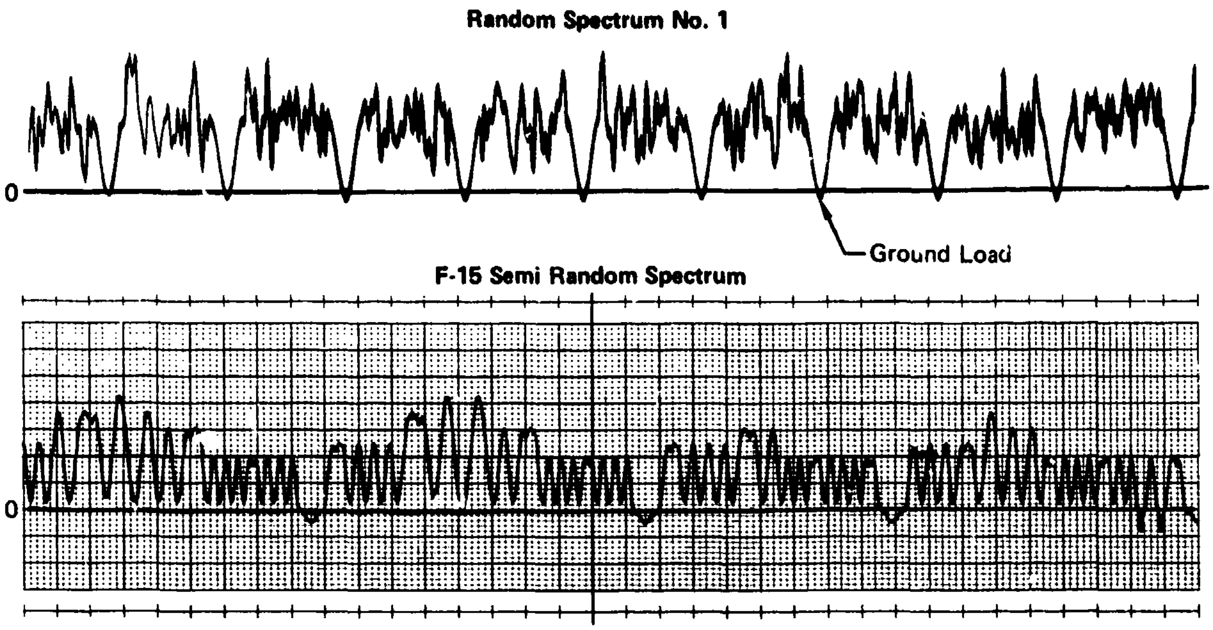


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FIGURE 63 EXAMPLE TIME HISTORY OF A-G MISSIONS

Spectrum	Percent Design Limit		N_p	N_o/N_p
	Mean	RMS		
Random Spectrum No. 1				
Air-To-Air	40%	15%	6,250	0.51
Air-To-Ground	31%	12%	4,500	0.59
Random Spectrum No. 2				
Same as No. 1 Plus				
Air-To-Air	30%	7%	52,318	0.51
Air-To-Ground	30%	7%	13,736	0.59

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FIGURE 64 PARAMETERS FOR DIFFERENT RANDOM SPECTRA

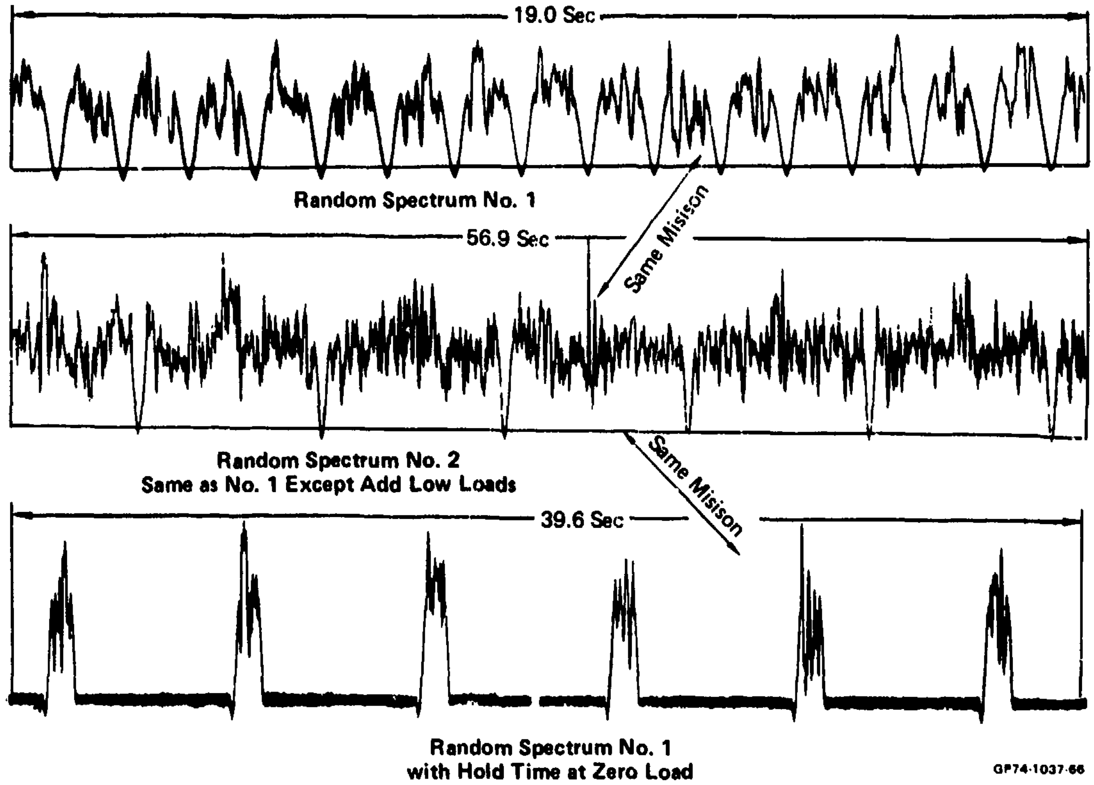

FIGURE 65 COMPARISON OF VARIATIONS IN RANDOM SPECTRUM

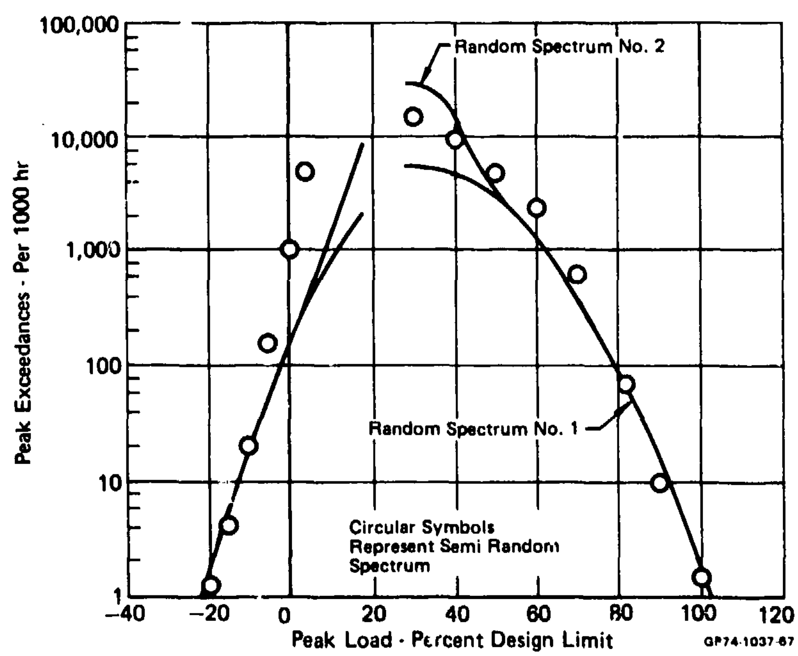

FIGURE 66 FATIGUE SPECTRA COMPARISON

SECTION 5

EXPERIMENTAL PROGRAM

In this program 34 static strength tests, 104 fatigue tests, and 50 residual strength tests were conducted. Test procedures and results are presented in the three paragraphs below. The mean, standard deviation and coefficient of variation for each of the data sets is presented. Standard formulas were used in their determination for the static strength data. Graphical procedures were used for the lifetime and residual strength data to compensate for fatigue life runouts and premature residual strength failures.

5.1 Static Strength Tests

All static strength testing was done on a Baldwin 30,000 pound universal test machine and the test set-up is shown in Figure 67. All specimens were strain gauged and a deflection gauge was placed between the grips of the test machine. Load was applied continuously to failure at a rate of .050 in/min. Before any tests were run, the temperature and humidity in the lab were checked to insure that they were in the approved ranges (68-72°F and 50-70% relative humidity). Several specimens were tested at 350°F on the same machine and were enclosed in an air circulating oven. Specimens were heated to 350°F, held at this temperature for ten minutes and then loaded as described above. Restuls of tests of full scale step-lap, small scale step-lap and simple specimens are presented in Tables 11 through 14. Results of 27 static strength tests run under the verification task are presented in Table 2 in Section 2.

5.2 Fatigue Life Tests

Each fatigue test was done in one of three 150,000 pound fatigue machines (see Figure 68). Hydraulic load cylinders were each controlled by a load feedback servo system programmed by a magnetic tape function generator. A strip chart recorder was used to make a continuous record of both the programmed signal and the loading applied during the test. The temperature and humidity of the air around the specimens were controlled so that they were within the required ranges.

Four tapes, numbers 1, 2, 3, 4, were used in the conduct of these tests. Tape 1 is the baseline spectrum called Random Spectrum #1 in Section 4. Tape 2 has a considerable number of low load levels added to Tape 1 and is called Random Spectrum #2 in Section 4. Tape 3 is the same as Tape 1 with frequency of load application reduced by a factor of eight. Tape 4 is the same as Tape 1 with hold time between missions increased by a factor of ten.

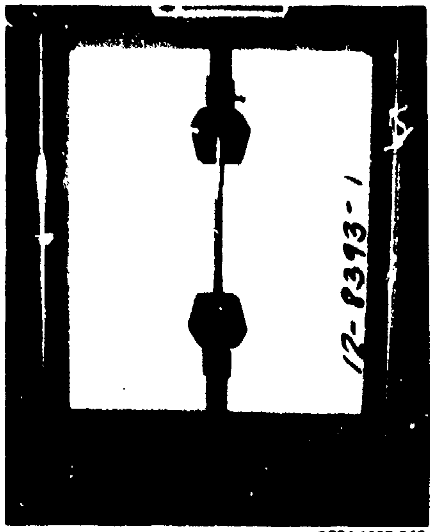

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FIGURE 67 STATIC STRENGTH TEST SETUP

TABLE 11 STATIC STRENGTH TESTS OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE

Reference No.	Specimen No.	Failure Load (lb)	Width (in.)	Running Load at Failure (lb/in.)	Laminate Strain at Failure (in./in. x 10^{-6})
1	1	21,775	0.9979	21,821	7,235
2	2	21,250	0.9998	21,254	6,890
3	3	21,300	1.0021	21,255	6,735
4	49	19,000	1.0070	18,868	6,360
5	81	20,925	1.0053	20,815	6,993
6	82	20,300	1.0081	20,137	6,640
7	83	16,640	1.0071	16,523	5,560
8	84	20,900	1.0066	20,763	7,200
9	85	20,550	1.0078	20,391	6,680
10	86	19,300	1.0050	19,204	6,480
			Mean	20,103	
			Standard Deviation	1,556	
			Coefficient of Variation	0.077	

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TABLE 12 STATIC STRENGTH TESTS OF FULL SCALE STEP-LAP SPECIMENS AT 350°F

Reference No.	Specimen No.	Failure Load (lb)	Width (in.)	Running Load at Failure (lb/in.)	Laminate Strain at Failure (in./in. x 10^{-6})
1	61	15,750	1.0014	15,728	5400
2	62	16,275	1.0019	16,244	5610
3	63	16,125	0.9992	16,138	5265
4	64	15,775	0.9992	15,788	5280
5	65	16,490	1.0004	16,483	5397
6	66	16,240	1.0038	16,179	5247
			Mean	16,093	
			Standard Deviation	287	
			Coefficient of Variation	0.018	

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TABLE 13 STATIC STRENGTH TESTS OF SMALL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE

Reference No.	Specimen No.	Failure Load (lb)	Width (in.)	Running Load at Failure (lb/in.)	Laminate Strain at Failure (in./in. x 10^{-6})
1	1	15,450	1.0038	15,392	7,745
2	2	17,650	1.0039	17,581	8,960
3	3	16,400	1.0099	16,239	9,520
4	36A	18,300	1.0024	18,256	9,000
5	65	18,750	1.0060	18,638	8,500
6	66	18,575	1.0049	18,484	8,600
7	67	17,325	1.0037	17,261	8,240
8	68	17,100	1.0045	17,023	8,200
9	69	17,050	1.0056	16,955	7,920
10	70	17,800	1.0066	17,683	8,600
			Mean	17,351	
			Standard Deviation	1,015	
			Coefficient of Variation	0.058	

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TABLE 14 STATIC STRENGTH TESTS OF SIMPLE SPECIMENS AT ROOM TEMPERATURE

Reference No.	Specimen No.	Failure Load (lb)	Width (in.)	Running Load at Failure (lb/in.)	Laminate Strain at Failure (in./in. x 10^{-6})
1	7	6,025	1.0029	6,008	8,000
2	25	6,450	0.9980	6,463	8,385
3	83	5,325	1.0017	5,316	6,960
4	20	6,425	0.9997	6,427	8,295
5	58	6,525	1.0037	6,501	8,750
6	84	5,475	1.0018	5,465	7,020
7	73	5,275	1.0010	5,270	7,455
8	46	6,475	1.0045	6,446	9,366
			Mean	5,987	
			Standard Deviation	552	
			Coefficient of Variation	0.092	

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GP74-1037-[illegible]48

FIGURE 68 FATIGUE TEST MACHINE

Load levels used were selected with test limit load (TLL) in a 60-70% range of average static strength to produce failures at about four lifetimes using Tape 1. This was done because the F-15 low cost production flight wing, the conceptual structural application, was to be designed for four lifetimes. The TLL selected for the full scale step-lap specimens is 13,500 (lb/in) which is 35% greater than the minimum required design limit load (DLL) of 10,000 (lb/in). If failure did not occur prior to six lifetimes, testing was stopped and the residual strength was determined at that point.

The high temperature tests were conducted on the same machines and were enclosed in an air circulating oven. The specimens were heated to 350°F, held at this temperature for ten minutes, and then tested to failure. Results of lifetime tests of full scale step-lap, small scale step-lap and simple specimens are presented in Tables 15 thru 22. The results of the 29 lifetime tests run under the verification task using the F-15 semi random wing root bending moment spectrum are presented in Table 3 (Section 2).

5.3 Residual Strength

Each residual strength specimen was fatigue tested in one of three 150,000 pound fatigue machines for the required number of lifetimes, then removed and failed statically in a Baldwin 30,000 pound universal test machine.

Results of residual strength tests of full scale step-lap, small scale step-lap and simple specimens are presented in Tables 23 thru 27.

5.4 Failure Analysis

Each specimen tested under this contract was carefully examined and the failure surfaces were analyzed. All the simple specimens failed in a similar mode, partially adhesive and partially interlaminar. Typical failure surfaces are illustrated in Figure 69. The failure surfaces of the step-lap specimens fell into seven general classifications. These are listed below:

Type A - cohesive failure on tang

Type B - adhesive failure on tang

Type C - partial interlaminar failure on tang

Type D - interlaminar failure on tang

Type E - adhesive failure on tang and adjoining step

Type F - cohesive failure on tang and adjoining step

Type G - titanium failure on tang

Each type failure surface is illustrated in Figure 70. In Figure 71 the failure modes of each step-lap specimen are identified by type.

TABLE 15 FATIGUE LIFE OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE BASELINE SPECTRUM

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Lifetimes	Last Load (% TLL)	Residual Strength (lb)
1	4	13,700	0.9983	2.5000*	115.0	
2	5	13,700	0.9981	3.1425*	95.0	
3	6	13,500	1.0013	3.0325	95.0	
4	7	13,500	1.0016	4.1250	85.0	
5	8	13,500	0.9983	5.5927	85.0	
6	9	13,500	0.9953	4.5000	115.0	
7	14	13,500	1.0112	6.0		18,900
8	15	13,500	1.0089	6.0		19,620
9	16	13,500	1.0020	6.0		13,960
10	17	13,500	0.9993	3.5000	115.0	
11	18	13,500	1.0026	6.0		18,720
12	24	13,500	1.0045	6.0		18,260
13	25	13,500	1.0053	6.0		17,870
14	26	13,500	1.0059	5.6070	95.0	
15	27	13,500	1.0030	5.1510	100.0	
16	28	13,500	1.0016	6.0		14,540
17	29	13,500	1.0043	6.0		19,800
18	30	13,500	1.0038	6.0		18,940
19	31	13,500	1.0063	5.4010	100.0	
20	32	13,500	1.0071	6.0		20,920
21	33	13,500	1.0072	6.0		19,770
22	34	13,500	1.0067	6.0		21,680
23	35	13,500	1.0070	6.0		17,700
24	19	13,500	1.0029	5.5000	95.0	
25	48	13,500	1.0012	3.1123	87.5	
26	50	13,500	1.0064	2.0000	90.0	
27	79	13,500	1.0065	2.0000	125.0	
28	87	13,500	1.0047	1.5000	115.0	
29	88	13,500	1.0048	2.5000	115.0	
30	89	13,500	1.0039	2.0000	125.0	
			Mean	5.8100		
			Standard Deviation	2.8800		
			Coefficient of Variation	0.496		

GP74-1037-97

*Not included in determination of mean since it corresponds to a different TLL.

TABLE 16 FATIGUE LIFE OF FULL SCALE STEP-LAP SPECIMENS AT 350°F BASELINE SPECTRUM

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Lifetimes	Last Load (% TLL)	Residual Strength (lb)
1	75	10,100	1.0094	6.0000		18,750 (1)
2	67	10,500	1.0031	6.0000		16,500
3	68	11,000	1.0052	6.0000		12,850
4	69	11,000	1.0042	6.0000		12,800
5	70	12,000	1.0051	2.0000	125	
6	76	11,500	1.0077	3.0315	100	

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(1) Specimen was tested at room temperature.

(2) No statistical parameters are presented because there is insufficient data with a common TTL.

TABLE 17 FATIGUE LIFE OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE FREQUENCY OF LOAD APPLICATION SLOWED TO 1/8 OF BASELINE

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Lifetimes	Last Load (% TLL)	Residual Strength (lb)
1	12	13,500	1.0088	5.1820	95	
2	13	13,500	1.0109	4.1258	90	
3	20	13,500	1.0020	2.0000	125	
4	21	13,500	1.0032	3.2580	95	
5	22	13,500	1.0039	6.0000		18,660
6	23	13,500	1.0043	6.0000		14,840
			Mean	4.7200		
			Standard Deviation	2.5600		
			Coefficient of Variation	0.542		

GP74-1037-99

TABLE 18 FATIGUE LIFE OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE ADDITIONAL LOW LOADS INCLUDED

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Lifetimes	Last Load (% TLL)
1	10	13,500	0.9987	1.4060	100
2	11	13,500	1.0082	2.0000	125
3	80	13,500	1.0063	1.6543	100
			Mean	1.6868	
			Standard Deviation	0.2983	
			Coefficient of Variation	0.177	

GP74-1037-101

TABLE 19 FATIGUE LIFE OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE RELAXATION TIME INCREASED TO TEN TIMES BASELINE

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Lifetimes	Last Load (% TLL)
1	56	13,500	1.0086	0.5000	115
2	57	13,500	1.0044	1.5000	115
3	71	13,500	1.0090	3.1108	95
4	72	13,500	1.0094	4.5000	115
5	73	13,500	1.0103	3.5000	115
6	74	13,500	1.0096	2.0000	125
			Mean	2.5185	
			Standard Deviation	1.4574	
			Coefficient of Variation	0.579	

GP74-1037-100

TABLE 20 FATIGUE LIFE OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE WITHOUT 115% AND 125% TLL LOADS

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Lifetimes	Last Load (% TLL)
1	77	13,500	1.0080	4.1510	100
2	78	13,500	1.0073	4.1510	100
3	90	13,500	1.0048	1.1645	100
			Mean	2.5185	
			Standard Deviation	1.3930	
			Coefficient of Variation	0.752	

GP74-1037-102

TABLE 21 FATIGUE LIFE OF SMALL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE BASELINE SPECTRUM

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Lifetimes	Last Load (% TLL)	Residual Strength (lb)
1	4	9,280	0.9996	6.0*		16,550
2	5	9,280	1.0068	6.0*		17,025
3	11	10,500	1.0095	6.0*		15,825
4	12	10,500	1.0003	6.0*		13,975
5	13	11,500	1.0095	4.0550	84.2	
6	6	11,500	1.0055	5.0000	92.1	
7	7	11,500	1.0050	3.5000	115.0	
8	8	11,500	1.0073	2.0000	125.0	
9	9	11,500	1.0059	2.0000	125.0	
10	10	11,500	1.0072	2.0000	125.0	
11	14	11,500	1.0092	5.0303	90.0	
12	15	11,500	1.0007	5.5000	115.0	
13	16	11,500	1.0029	5.2750	92.5	
14	17	11,500	1.0059	4.5000	115.0	
15	18	11,500	1.0079	5.1798	90.0	
16	19	11,500	1.0100	6.0		13,375
17	20	11,500	1.0079	5.4010	90.0	
18	21	11,500	1.0051	3.5000	115.0	
19	22	11,500	1.0073	3.8913	80.0	
20	23	11,500	1.0078	2.4050	82.2	
21	24	11,500	1.0054	2.0000	125.0	
22	25	11,500	1.0057	3.4057	87.5	
23	26	11,500	1.0067	2.0000	125.0	
24	27	11,500	1.0071	4.1510	92.5	
25	28	11,500	1.0063	1.8118	92.5	
26	29	11,500	1.0074	2.0000	125.0	
27	30	11,500	1.0056	6.0		13,775
28	31	11,500	1.0076	4.7815	100.0	
29	32	11,500	1.0087	1.9013	95.0	
30	33	11,500	1.0089	2.0000	125.0	
31	34	11,500	1.0093	4.5000	115.0	
32	35	11,500	1.0071	2.5000	115.0	
33	37	11,500	1.0069	2.6483	90.0	
34	38	11,500	1.0041	1.9018	90.0	
35	39	11,500	1.0069	4.1050	115.0	
36	40	11,500	1.0077	4.8025	75.0	
37	41	11,500	1.0004	3.5000	115.0	
38	42	11,500	1.0029	4.3935	80.0	
39	43	11,500	1.0008	1.7698	82.5	
40	64	11,500	1.0051	2.2505	82.5	
			Mean	3.5500		
			Standard Deviation	1.7480		
			Coefficient of Variation	0.492		

GP74-1037-95

*Not included in calculation of the mean since it corresponds to a different TLL.

TABLE 22 FATIGUE LIFE OF SIMPLE SPECIMENS AT ROOM TEMPERATURE BASELINE SPECTRUM

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Lifetimes	Last Load (% TLL)
1	71	3,600	1.0013	1.3525*	100
2	16	3,600	0.9994	3.6500*	110
3	88	3,480	1.0011	2.1700	95
4	30	3,600	1.0009	2.3750*	100
5	21	3,480	0.9988	4.4250	95
6	32	3,480	1.0011	4.7700	97.5
7	6	3,480	1.0028	1.6850	95
8	24	3,480	0.9989	4.5625	95
9	66	3,480	1.0040	3.0200	95
10	23	3,480	0.9983	4.5000	95
			Mean	3.5904	
			Standard Deviation	1.2802	
			Coefficient of Variation	0.357	

GP74-1037-93

*Not included in calculation of mean because it corresponds to a different TLL.

TABLE 23
THREE LIFETIME RESIDUAL STRENGTH OF FULL SCALE STEP-LAP SPECIMEN AT ROOM TEMPERATURE BASELINE SPECTRUM

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Residual Run Load (lb/in.)	Lifetimes	Last Load (% TLL)	Residual Strength (lb)
1	36	13,500	1.0047	20,086	3.0000		20,180
2	37	13,500	1.0049	18,400	3.0000		18,490
3	38	13,500	1.0067	21,327	3.0000		21,470
4	39	13,500	1.0062	21,258	3.0000		21,390
5	40	13,500	1.0070	18,620	3.0000		18,750
6	41	13,500	1.0038	16,736	3.0000		16,800
7	42	13,500	1.0093	18,458	3.0000		18,630
8	43	13,500	1.0093	16,566	3.0000		16,720
9	92	13,500	1.0073		2.0000	125	
10	99	13,500	0.9988	16,470	3.0000		16,450
11	44(1)	13,500	1.0081		1.1505	95	
12	45(1)	13,500	0.9969		1.2500	95	
			Mean	18,250			
			Standard Deviation	2,760			
			Coefficient of Variation	0.151			

(1) Rejected by NDT

GP75-0332-45

TABLE 24
TWO LIFETIME RESIDUAL STRENGTH OF FULL SCALE STEP-LAP SPECIMEN AT ROOM TEMPERATURE BASELINE SPECTRUM

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Residual Running Load (lb/in.)	Lifetimes	Last Load (% TLL)	Residual Strength (lb)
1	91	13,500	1.0082	18,250	2.0000		18,400
2	93	13,500	1.0085	18,304	2.0000		18,460
3	94	13,500	1.0057		0.5000	115	
4	95	13,500	1.0051		1.5000	115	
5	96	13,500	1.0010	17,023	2.0000		17,040
6	97	13,500	1.0011		1.5000	115	
7	55	13,500	1.0086	16,458	2.0000		16,600
8	98	13,500	1.0006		1.5000	115	
9	100	13,500	0.9991	12,651	2.0000		12,640
10	60	13,500	1.0030	15,479	2.0000		15,525
11	46(1)	13,500	0.9980		1.0611	95	
12	47(1)	13,500	1.0048		0.8623	90	
13	51(1)	13,500	1.0050		0.0005	80	
14	52(1)	13,500	1.0042		0.4010	90	
15	53(1)	13,500	1.0089		0.3615	95	
16	54(1)	13,500	1.0053		0.5000	115	
17	58(1)	13,500	1.0067		0.9010	95	
18	59(1)	13,500	1.0086		1.9020	100	
			Mean	14,650			
			Standard Deviation	3,808			
			Coefficient of Variation	0.260			

(1) Rejected by NDT

TABLE 25 TWO LIFETIME RESIDUAL STRENGTH OF SMALL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE BASELINE SPECTRUM

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Residual Running Load (lb/in.)	Lifetimes	Last Load (% TLL)	Residual Strength (lb)
1	53	11,500	0.9991	16,100	2.0000		16,115
2	54	11,500	0.9997	16,000	2.0000		16,005
3	55	11,500	1.0017		1.4018	105.0	
4	56	11,500	1.0000	15,000	2.0000		15,000
5	57	11,500	0.9976	12,000	2.0000		12,029
6	58	11,500	0.9979		0.5000	115.0	
7	59	11,500	0.9976		1.5000	115.0	
8	60	11,500	0.9956		1.6500	95.0	
9	61	11,500	1.0029		1.0163	87.5	
10	62	11,500	0.9883		1.5000	115.0	
			Mean	11,800			
			Standard Deviation	3,840			
			Coefficient of Variation	0.326			

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TABLE 26 THREE LIFETIME RESIDUAL STRENGTH OF SMALL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE BASELINE SPECTRUM

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Residual Running Load (lb/in.)	Lifetimes	Last Load (% TLL)	Residual Strength (lb)
1	44	11,500	1.0027		1.0543	95.0	
2	45	11,500	1.0012		2.0000	125.0	
3	46	11,500	1.0030		1.5000	115.0	
4	47	11,500	1.0049	13,185	3.0000		13,250
5	48	11,500	1.0032		2.0000	115.0	
6	49	11,500	1.0033		1.3750	95.0	
7	50	11,500	1.0005		1.1500	92.5	
8	51	11,500	0.9972	16,245	3.0000		16,200
9	52	11,500	0.9997		1.1250	90.0	
10	63	11,500	1.0064		1.0313	95.0	
			Mean	6,820			
			Standard Deviation	7,128			
			Coefficient of Variation	1.044			

GP74-1037-104

TABLE 27 THREE LIFETIME RESIDUAL STRENGTH OF SIMPLE SPECIMENS AT ROOM TEMPERATURE BASELINE SPECTRUM

Reference No.	Specimen No.	Test Limit Load (lb)	Width (in.)	Residual Running Load (lb/in.)	Lifetimes	Last Load (% TLL)	Residual Strength (lb)
1	87	3,480	1.0023		2.1100	57.9	
2	49	3,480	1.0040	6,449	2.0000		6,475
3	57	3,480	1.0031	5,209	3.0000		5,225
4	79	3,480	1.0015	4,119	3.0000		4,125
5	54	3,480	1.0020	5,190	3.0000		5,200
6	63	3,480	1.0031		2.0000	125.0	
7	72	3,480	1.0013		2.5000	115.0	
8	47	3,480	1.0044	6,272	3.0000		6,300
9	90	3,480	1.0029		2.0500	81.5	
10	85	3,480	0.9939		2.2900	92.5	
			Mean	4,100			
			Standard Deviation	2,212			
			Coefficient of Variation	0.540			

GP74-1037-103

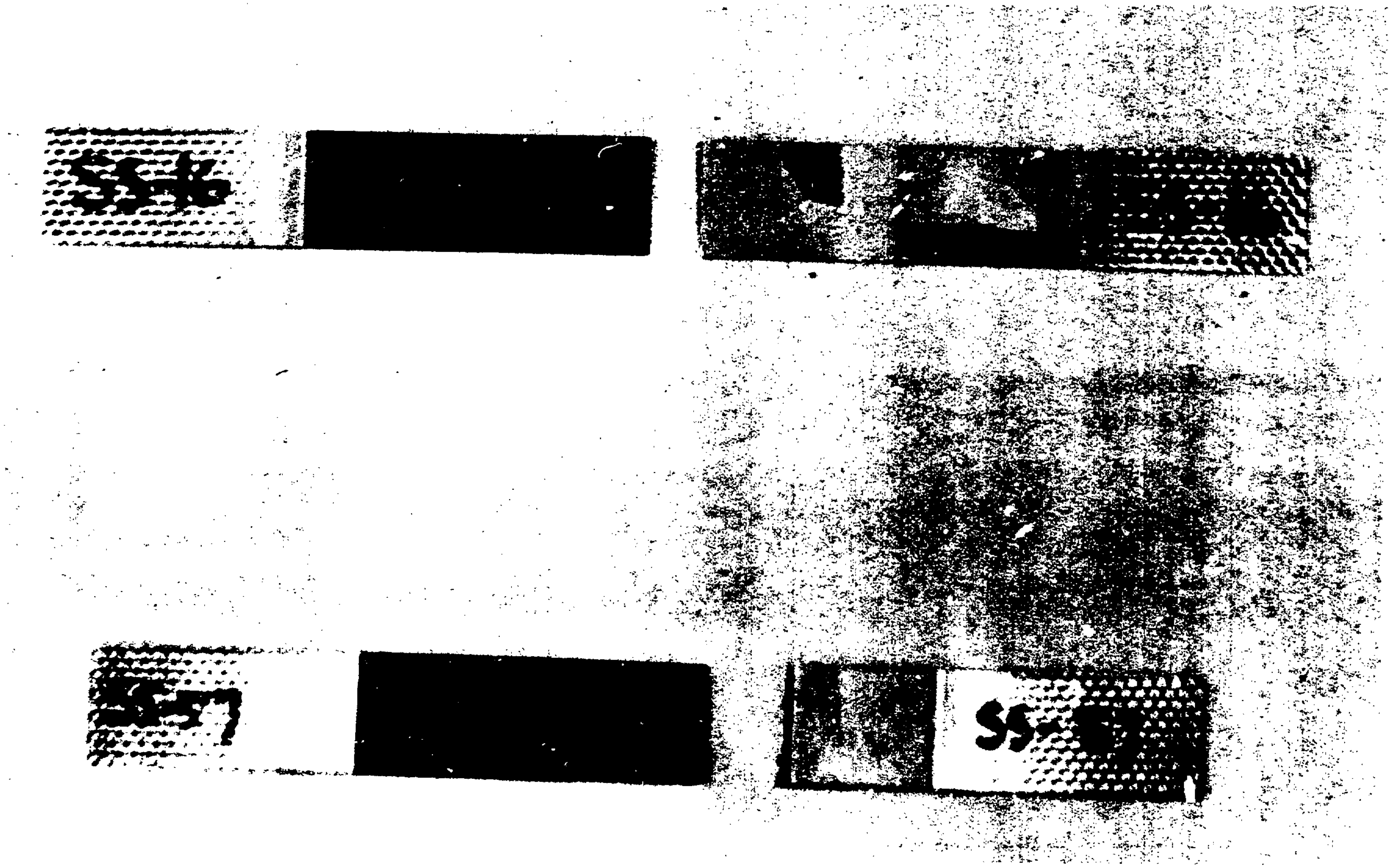
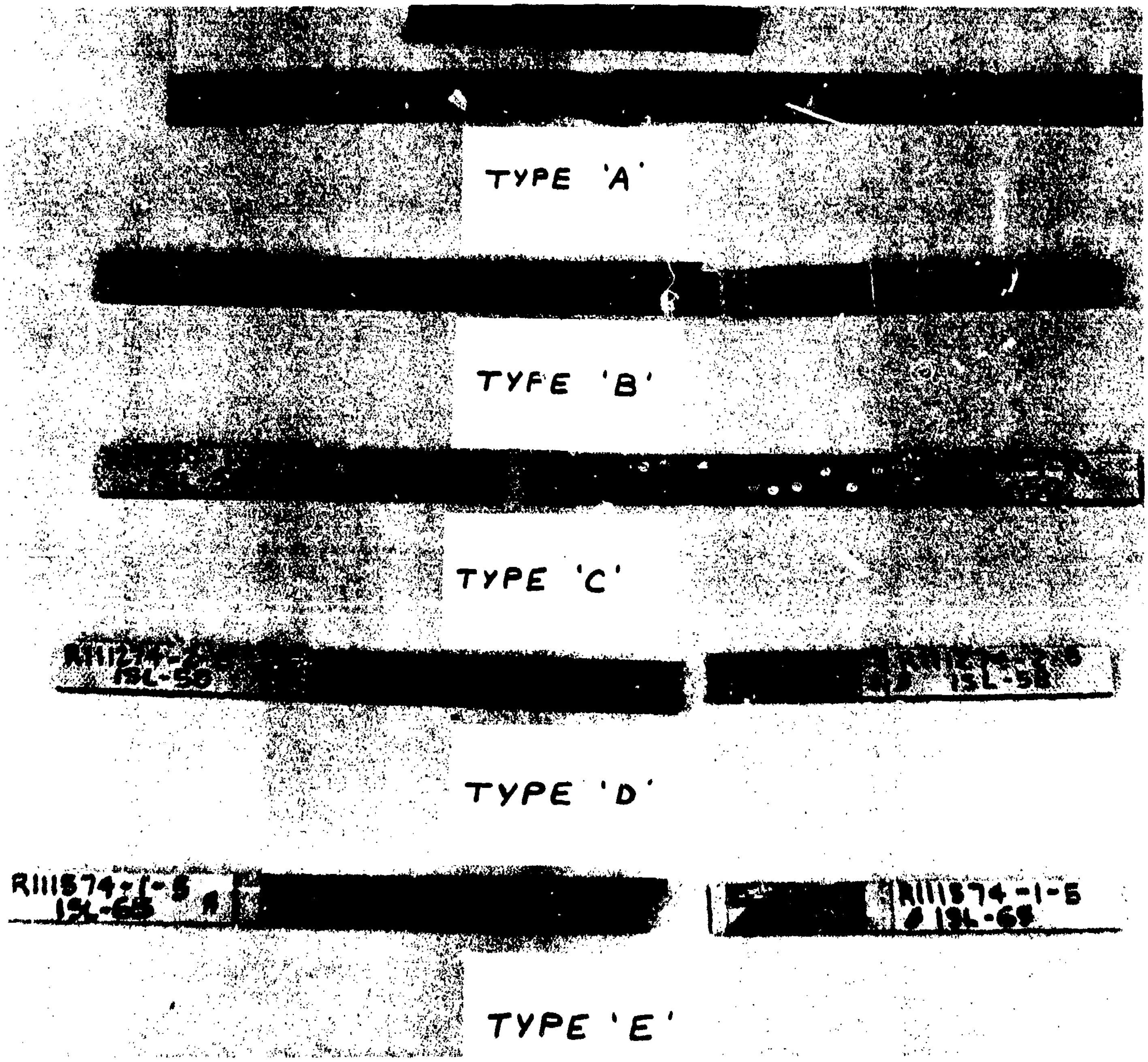
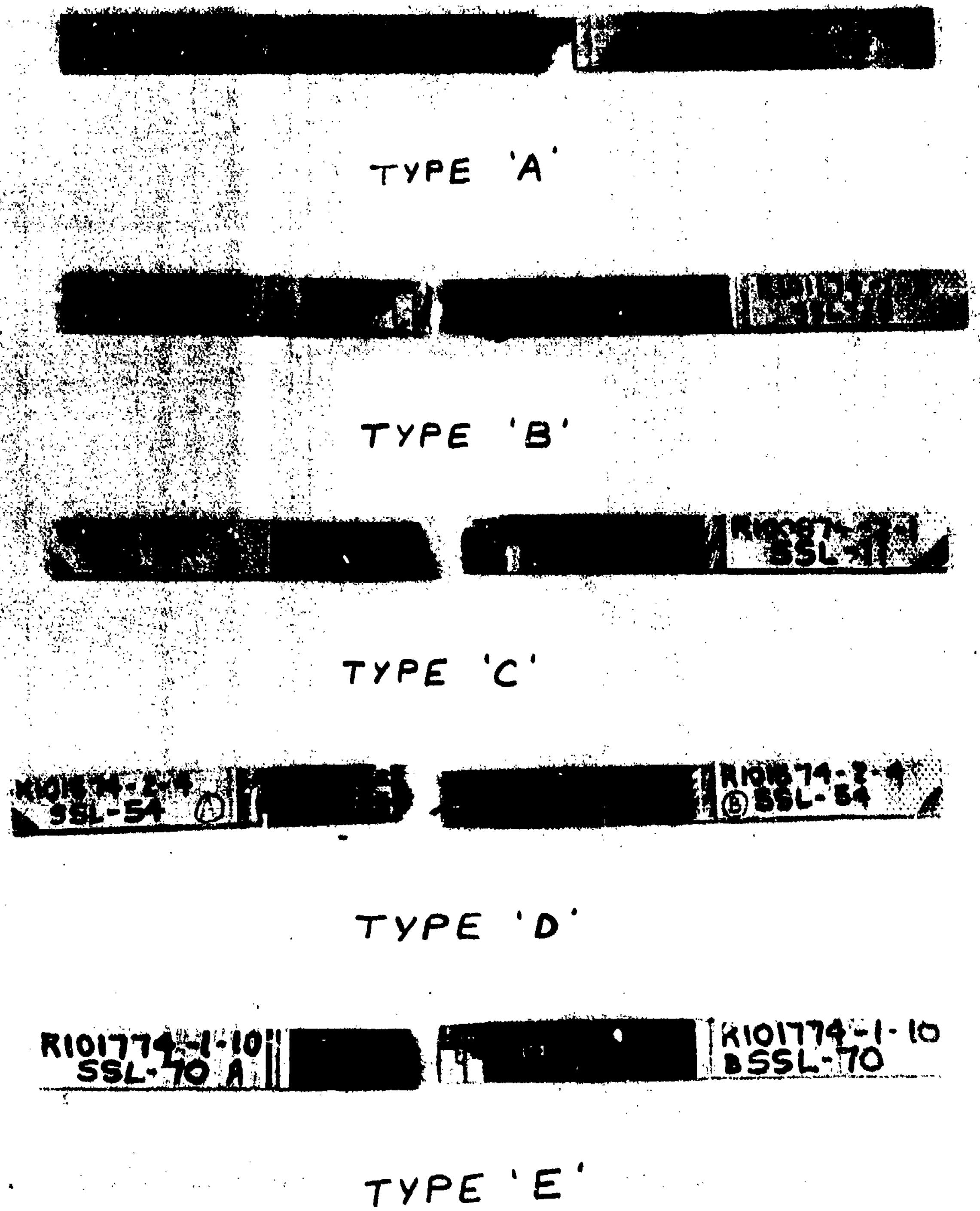


FIGURE 69 TYPICAL FAILURE MODE FOR SIMPLE SPECIMENS



Full Scale Step-Lap Specimens

FIGURE 70 TYPICAL FAILURE MODES FOR STEP-LAP SPECIMENS



Small Scale Step-Lap Specimens

FIGURE 70 TYPICAL FAILURE MODES FOR STEP-LAP SPECIMENS (Continued)

Full Scale Step-Lap No.	Type	Small Scale Step-Lap No.	Type	Full Scale Step-Lap No.	Type	Small Scale Step-Lap No.	Type	Full Scale Step-Lap No.	Type	Small Scale Step-Lap No.	Type
1	D	1	D	31	B	31	B	61	F	61	A
2	D	2	D	32	D	32	A	62	A	62	B
3	C	3	D	33	C	33	A	63	F	63	B
4	A	4	D	34	D	34	B	64	F	64	B
5	A	5	D	35	D	35	A	65	F	65	D
6	B	6	A	36	D	36A	D	66	F	66	C
7	B	7	A	37	D	37	B	67	F	67	C
8	B	8	B	38	D	38	B	68	A	68	C
9	B	9	B	20	D	39	B	69	F	69	C
10	B	10	A	40	B	40	B	70	F	70	G
11	A	11	C	41	D	41	A	71	F		
12	B	12	B	42	D	42	A	72	B		
13	B	13	A	43	B	43	A	73	B		
14	B	14	B	44	C	44	D	74	C		
15	B	15	B	45	B	45	A	75	C		
16	C	16	B	46	A	46	D	76	F		
17	B	17	C	47	B	47	A	77	B		
18	A	18	B	48	A	48	A	78	B		
19	A	19	B	49	C	49	A	79	C		
20	C	20	A	50	C	50	A	80	C		
21	E	21	A	51	D	51	B	81	D		
22	B	22	A	52	D	52	B	82	D		
23	B	23	B	53	D	53	D	83	D		
24	B	24	B	54	D	54	D	84	C		
25	B	25	B	55	D	55	B	85	D		
26	B	26	B	56	D	56	C	86	D		
27	B	27	A	57	C	57	B	87	D		
28	E	28	B	58	D	58	C	88	D		
29	B	29	A	59	A	59	B	89	D		
30	B	30	A	60	D	60	B	90	C		

Notes:

(1) 20% failed in mode A
34.35% failed in mode B
13.75% failed in mode C
23.75% failed in mode D
1.25% failed in mode E
6.25% failed in mode F
0.65% failed in mode G

(2) This data could not be related to batch effects

(3) Type A - cohesive failure on tang
Type B - adhesive failure on tang
Type C - partial interlaminar failure on tang
Type D - interlaminar failure on tang
Type E - adhesive failure on tang and adjoining step
Type F - cohesive failure on tang and adjoining step
Type G - titanium failure on tang

FIGURE 71 IDENTIFICATION OF FAILURE MODES FOR STEP-LAP SPECIMENS

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SECTION 6

DATA REDUCTION

Static strength, residual strength and fatigue life are each assumed to be statistically distributed according to the Weibull probability function. This assumption is required in the development of the wearout model given in Appendix B. An evaluation of the data generated in this program indicates a favorable comparison with the Weibull distribution.

The probabilities given by the Weibull function are presented in the following equations:

$$P\,[F_s] = \exp - [F_s/\beta_s]^{\alpha_s} \tag{14}$$

$$P\,[F_R(T)] = \exp - [F_R(T)/\beta_R(T)]^{\alpha_R(T)} \tag{15}$$

$$P\,[T] = \exp - [T/\beta_f]^{\alpha_f} \tag{16}$$

Probabilities thus defined are that a given specimen will have a static strength equal to or greater than F_s, a residual strength at time T equal to or greater than $F_R(T)$, and a fatigue life equal to or greater than T. The terms α_s and β_s, $\alpha_R(T)$ and $\beta_R(T)$, and β_f and α_f are shape and scale parameters for static strength, residual strength at time T and fatigue life respectively. Scale and shape parameters for residual strength and fatigue life correspond to a given loading spectrum with specified load levels and environments. The Weibull scale parameter, β, plays a role similar to the mean of the normal distribution. Data scatter is related to $1/\alpha$, i.e., small values of the shape parameter α represent large scatter. Several procedures are available for the estimation of the scale and shape parameters of a Weibull distribution, e.g., Maximum Likelihood Estimation (MLE), Best Linear Unbiased (BLU) estimate and Menon's estimate. No consensus concerning the best procedure is found in the literature and a comparison of the parameters estimated using these procedures showed little difference. Since MCAIR has previously used the BLU procedure, Reference 16, it was used throughout this work.

6.1 BLU Procedure

The Best Linear Unbiased estimate for determination of parameters of the Weibull distribution is developed in Reference 30. Only the essentials required to make the estimates in this report are presented here. The table of weights used to make estimates is given in Reference 31. In this table N corresponds to the number of tests, M corresponds to the number of data points (failures) obtained and I is an ordering index where I = 1 corresponds to the smallest data point, I = 2 the next smallest, etc. For the assumed Weibull distribution given by equation (17)

$$P\,[F] = \exp - [F/\beta]^{\alpha} \tag{17}$$

the BLU estimates of the parameters are obtained from equations (18) and (19)

$$\alpha = [1 - E(LB)] \Big/ \sum_{I=1}^{M} C(N,M,I) \ln F_I \tag{18}$$

$$\beta = \exp \left[\sum_{I=1}^{M} A(N,M,I) \ln F_I + E(CP) \sum_{I=1}^{M} C(N,M,I) \ln F_I / [1 - E(LB)] \right] \tag{19}$$

The table contains values for $N \leq 25$. For sets in which there are more than 25 data points, the points should be randomly grouped into subsets with 25 or fewer data points. The set estimate is then taken to be the weighted average of the subsets where the weighting factor is the reciprocal of the term, γ, given in equation (20),

$$\gamma = E(LB)/[1 - E(LB)] \tag{20}$$

6.2 Scale and Shape Parameter Estimation

The estimation procedure described in Section 6.1 was used to generate Weibull shape and scale parameters for each of the static strength and fatigue life data sets presented in Section 5. The calculations used to get these estimates are presented in Appendix D. This procedure cannot be used to bias a residual strength distribution downward to account for the fact that some of the specimens may fail prior to the time at which the residual strength was to be measured. Each of the groups of specimens which were selected for residual strength tests at some predetermined time had premature failures of this type. The Weibull parameters for the residual strength data sets presented in Section 5 were thus determined graphically (see Appendix E). The measured residual strengths were ranked from highest to lowest and the probability of survival, P_S, was determined from equation (21)

$$P_S = \frac{n}{N+1} \tag{21}$$

where n is the rank of the data and N is the total number of specimens tested including the ones which failed prematurely. The resulting data was plotted as $\ln \ln \frac{1}{P_S}$ vs $\ln F_r$. A best fit straight line is then drawn through these points. The scale parameter is the value of F_r at which the resulting line intersects the $\ln \ln \frac{1}{P_S} = 0$ line. The shape parameter is the slope of this line. A summary of the parameters determined is presented in Table 28.

6.3 Transformation of Parameters to Single Variate

The specimens used in this program are double ended to facilitate load introduction. The weakest of the joints at each end will fail first. The Weibull parameters developed directly from the data may thus be considered as representing a least of two (L02) strength or fatigue life distribution. These were transformed to represent a single variate (SV) distribution by using equation (22)

$$\begin{aligned} \alpha_{SV} &= \alpha_{L02} \\ \beta_{SV} &= \beta_{L02} \exp \frac{1}{\alpha} \ln 2 \end{aligned} \tag{22}$$

as shown in Reference 8.

TABLE 28
SUMMARY OF WEIBULL PARAMETERS

Spec Type	Type Test	Spectrum Identification	Test Limit Load (lb/in.)	Data Source Table	Data Source No. of Spec	α	Weibull Parameters β (lb/in.) or Lifetimes Least of Two Variate	Weibull Parameters β (lb/in.) or Lifetimes Single Variate	Table of Calculations
Simple	Static Strength	N/A	N/A	14	8	14.66530	6,224	6,525	D1
	3.0 Life R.S.	Baseline	3,480	27	9	4.05000	4,890	5,803	–
	Lifetime	Baseline	3,480	22	7	3.53846	4.0360	4.9094	D2
Small	Static Strength	N/A	N/A	13	10	20.33760	17,831	18,449	D3
Scale	2.0 Life R.S.	Baseline	11,500	25	10	2.85710	12,772	16,279	–
Step-Lap	3.0 Life R.S.	Baseline	11,500	26	10	1.60000	9,414	14,518	–
	Lifetime	Baseline	11,500	21	36	2.52659	4.12828	5.4314	D4
Full	RT Static Str	N/A	N/A	11	10	17.96945	20,762	21,579	D5
Scale	350°F Static Str	N/A	N/A	12	6	59.55926	16,240	16,430	D6
Step-Lap	2.0 Life R.S.	Baseline	13,500	24	10	4.42300	15,329	17,930	–
	3.0 Life R.S.	Baseline	13,500	23	10	7.00000	19,341	21,354	–
	Lifetime	Baseline	13,500	15	28	2.19849	6.86920	9.4153	D7
	Lifetime	1/3 Base Load Freq	13,500	17	6	2.28462	5.61701	7.6080	D8
	Lifetime	Low Loads Incl	13,500	18	3	5.55864	1.84710	2.0924	D9
	Lifetime	10 x Base Freq	13,500	19	6	1.65186	2.97119	4.5203	D10
	Lifetime	High Loads Exclud	13,500	20	3	1.87371	3.70800	5.3678	D11

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6.4 Comparison of the Cumulative Frequencies with The Weibull Distributions

Comparison of the cumulative frequencies obtained from tests with the corresponding Weibull distributions for which there was a statistically significant data base is presented in Figures 72 through 75. The cumulative frequencies are represented by the circles on these figures. The comparison is favorable.

6.5 Development of the Wearout Models

The parameters of the wearout models, r and A_4, are determined from the Weibull parameters with the aid of equations (23).

$$r = \frac{\alpha_s}{2\alpha_F} + 1$$

$$A_4 = \frac{\beta_s^{2(r-1)}}{(r-1)\ \beta_F} \tag{23}$$

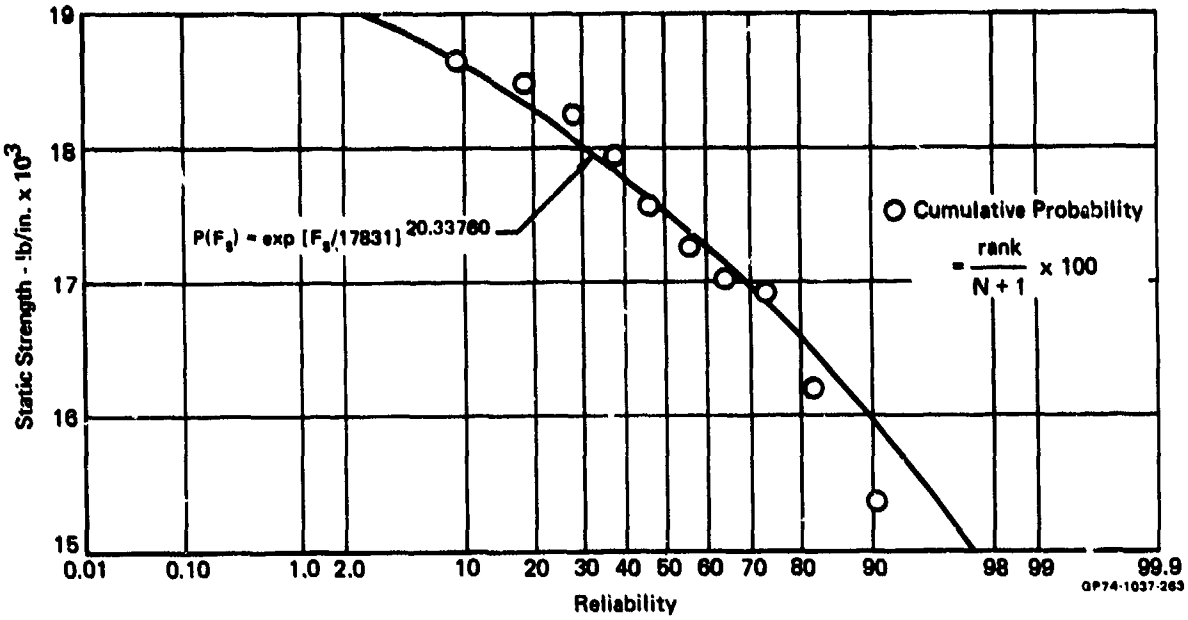

FIGURE 72 COMPARISON OF STATIC STRENGTH DATA FOR THE SMALL SCALE STEP-LAP SPECIMENS WITH CORRESPONDING WEIBULL DISTRIBUTION

These parameters along with the corresponding wearout models are summarized for each type specimen and each load condition in Table 29.

6.5 Evaluation of Wearout Models

The residual strength tests conducted under this contract were to provide data to evaluate the accuracy of the wearout models. The comparison of these data with the predictions of the wearout models is presented in Figures 76 thru 80. The solid lines in these figures represents the predictions of the wearout models. The circles represent the cumulative frequencies associated with each test point and the dashed lines correspond to Weibull distributions developed from the residual strength test data.

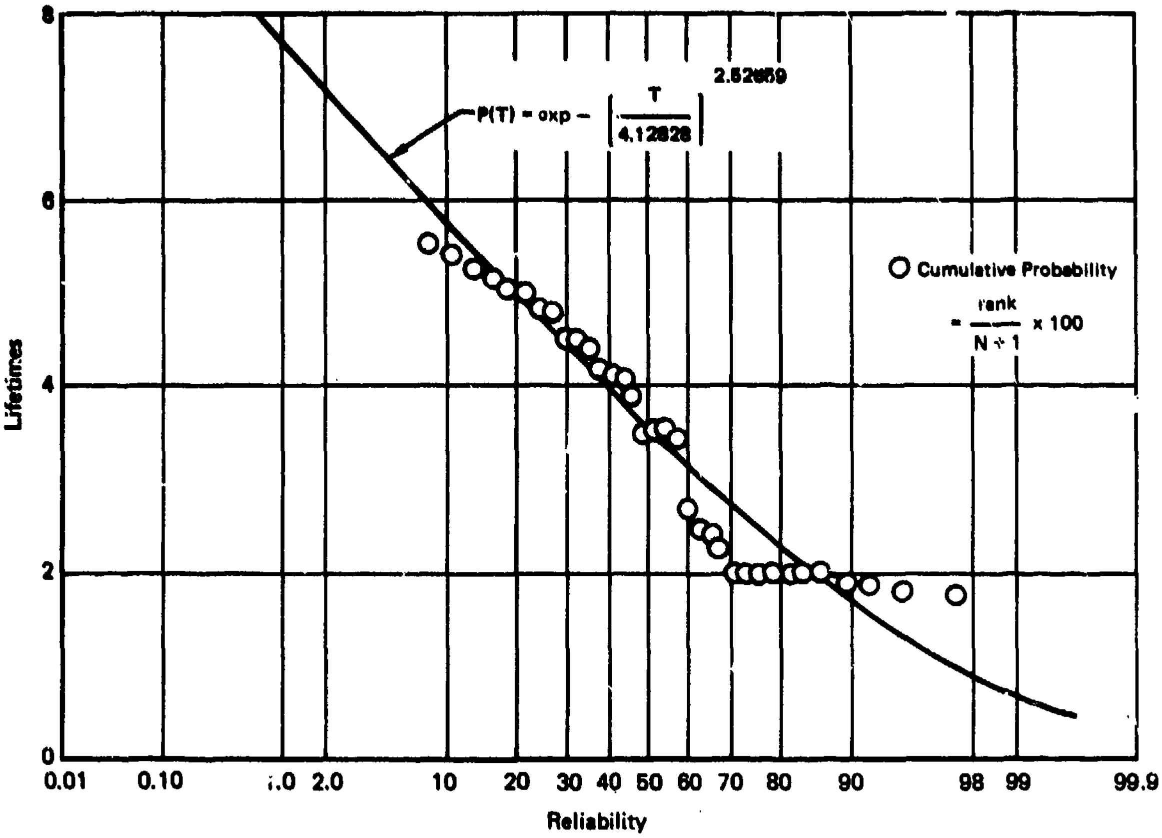

FIGURE 73 COMPARISON OF LIFETIME DATA FOR THE SMALL SCALE STEP-LAP SPECIMENS WITH CORRESPONDING WEIBULL DISTRIBUTION

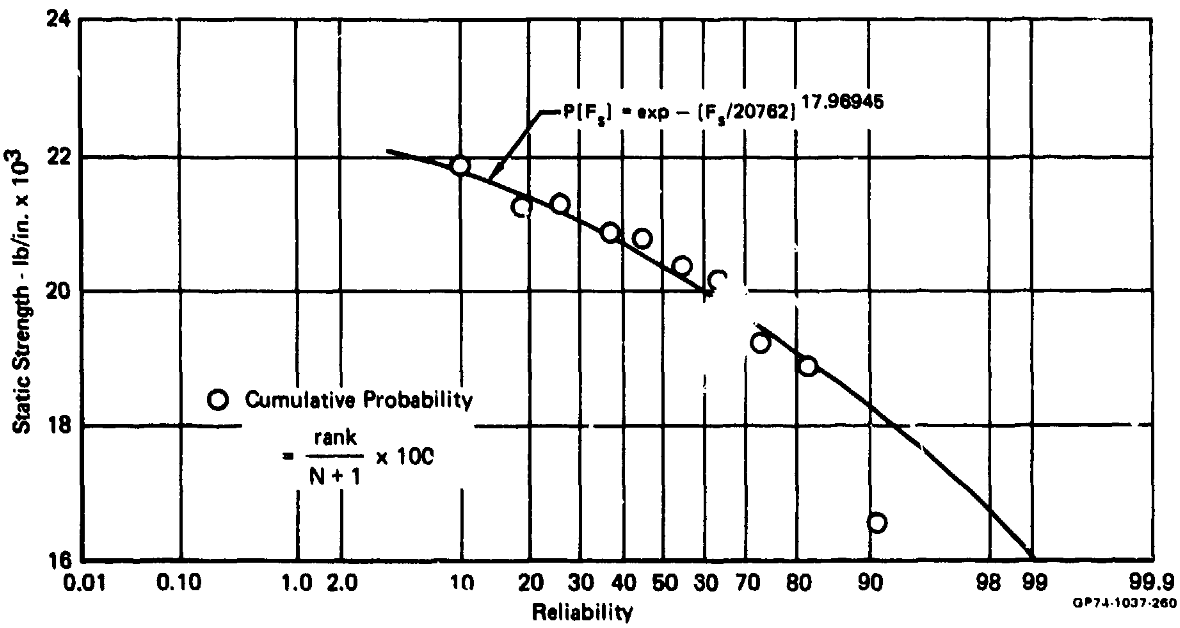

FIGURE 74 COMPARISON OF STATIC STRENGTH DATA FOR THE FULL SCALE STEP-LAP SPECIMENS WITH CORRESPONDING WEIBULL DISTRIBUTION

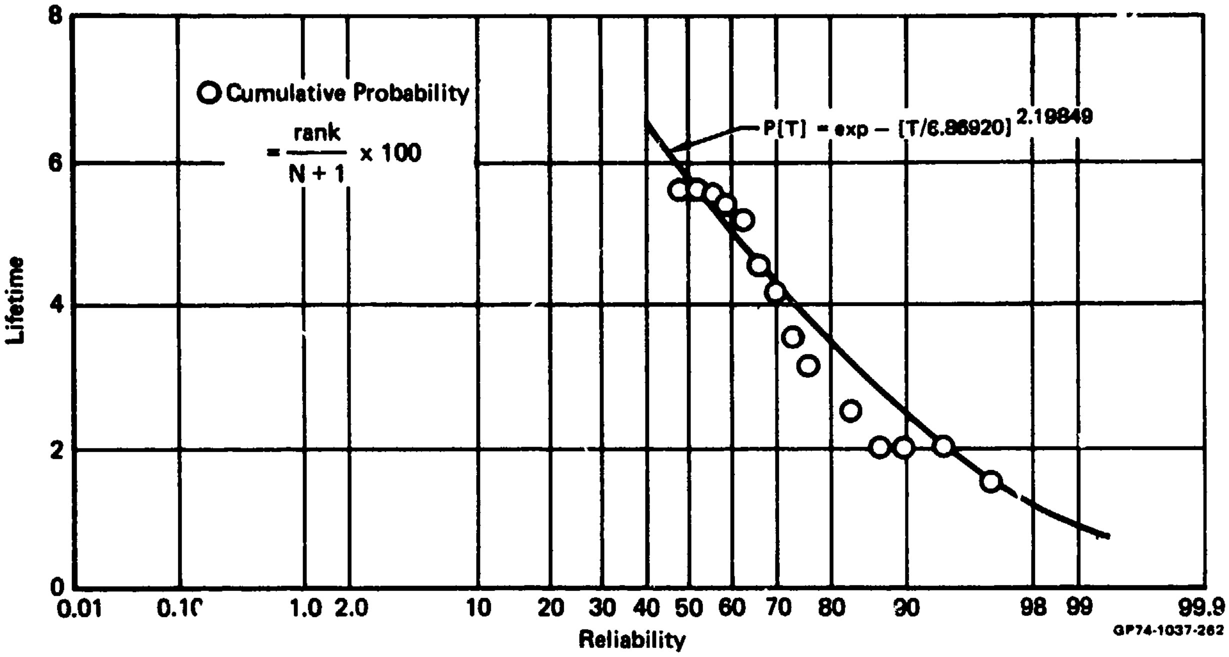

FIGURE 75 COMPARISON OF LIFETIME DATA FOR THE FULL SCALE STEP-LAP SPECIMENS WITH CORRESPONDING WEIBULL DISTRIBUTION

TABLE 29 SUMMARY OF THE WEAROUT MODELS AND THEIR PARAMETERS

Specimen Type	Spectrum/Ident	Test Limit Load (lb/in.)	Parameters: r	Parameters: A_4 $\left(\frac{\text{lb/in.} \times 10^4}{\text{Lifetimes}}\right)$	Wearout Models
Simple Spec	Baseline	3,480	3.07228	0.01675	$P[F] = \exp - \left[\frac{F^{4.14456} + 0.03471\,t}{0.14012}\right]^{3.53845}$
Small Scale Step-Lap	Baseline	11,500	5.02471	6.32871	$P[F] = \exp - \left[\frac{F^{8.04942} + 25.47122\,t}{105.15228}\right]^{2.52659}$
Full Scale Step-Lap	Baseline	13,500	5.08677	13.96131	$P[F] = \exp - \left[\frac{F^{8.17354} + 57.05666\,t}{391.93350}\right]^{2.19849}$
Full Scale Step-Lap	Freq 1/8 of Baseline	13,500	2.59956	1.15206	$P[F] = \exp - \left[\frac{F^{3.19912} + 1.84279\,t}{10.3510}\right]^{2.28462}$
Full Scale Step-Lap	Additional Low Loads	13,500	2.61635	3.55312	$P[F] = \exp - \left[\frac{F^{3.23270} + 5.74309\,t}{10.60806}\right]^{5.55864}$
Full Scale Step-Lap	High Loads Excluded	13,500	5.79515	62.05327	$P[F] = \exp - \left[\frac{F^{9.59030} + 297.55474\,t}{1103.33319}\right]^{1.87371}$
Full Scale Step-Lap	Relax. 10 x Baseline	13,500	6.43916	174.94173	$P[F] = \exp - \left[\frac{F^{10.87832} + 951.53606\,t}{2827.19484}\right]^{1.65186}$

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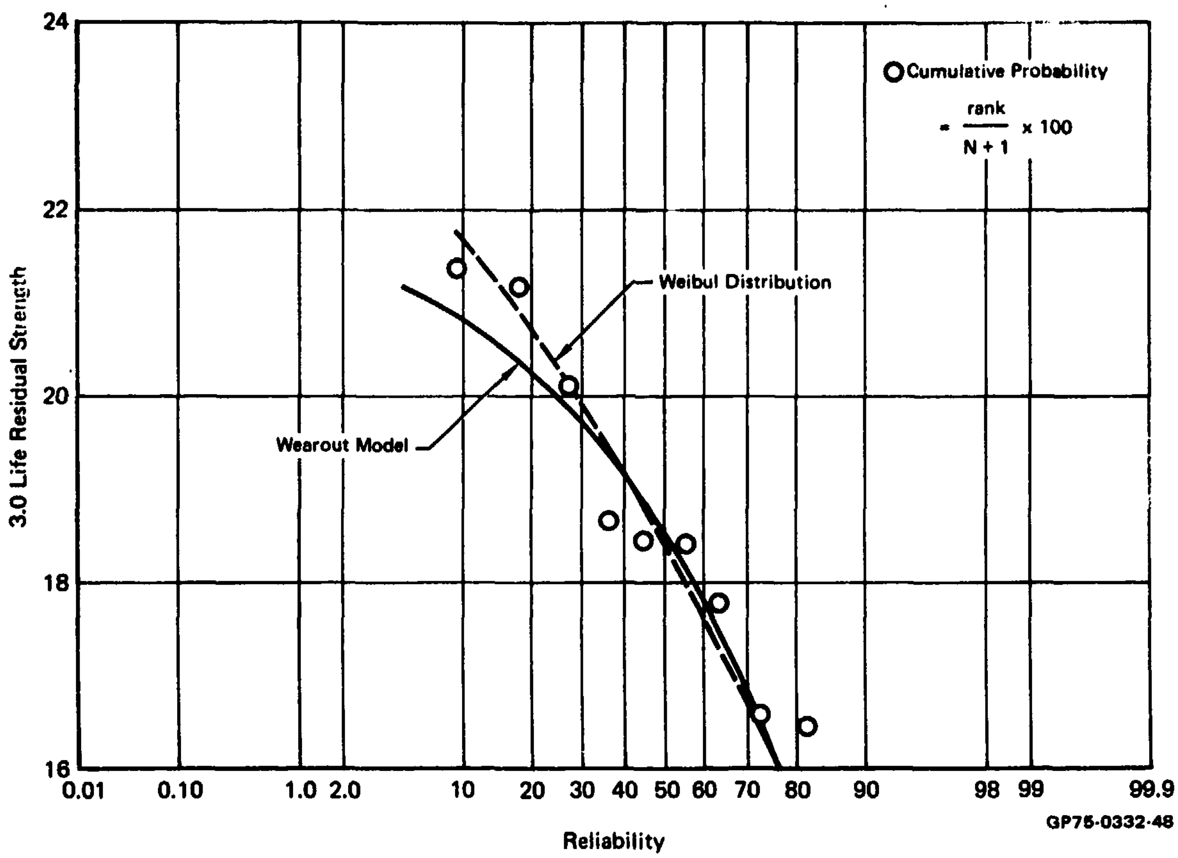

FIGURE 76 COMPARISON OF WEAROUT MODEL FOR FULL SCALE STEP-LAP SPECIMEN AT 3.0 LIFETIMES WITH WEIBULL DISTRIBUTIONS

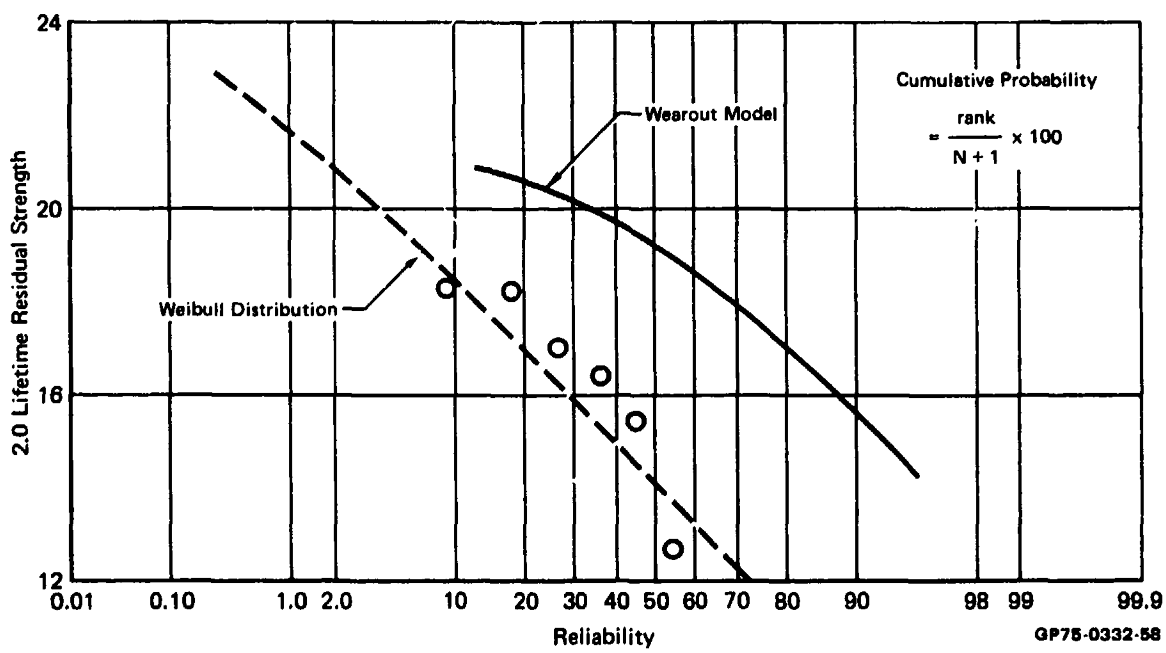

FIGURE 77 COMPARISON OF WEAROUT MODEL FOR FULL SCALE STEP-LAP SPECIMENS AT 2.0 LIFETIMES WITH WEIBULL DISTRIBUTION

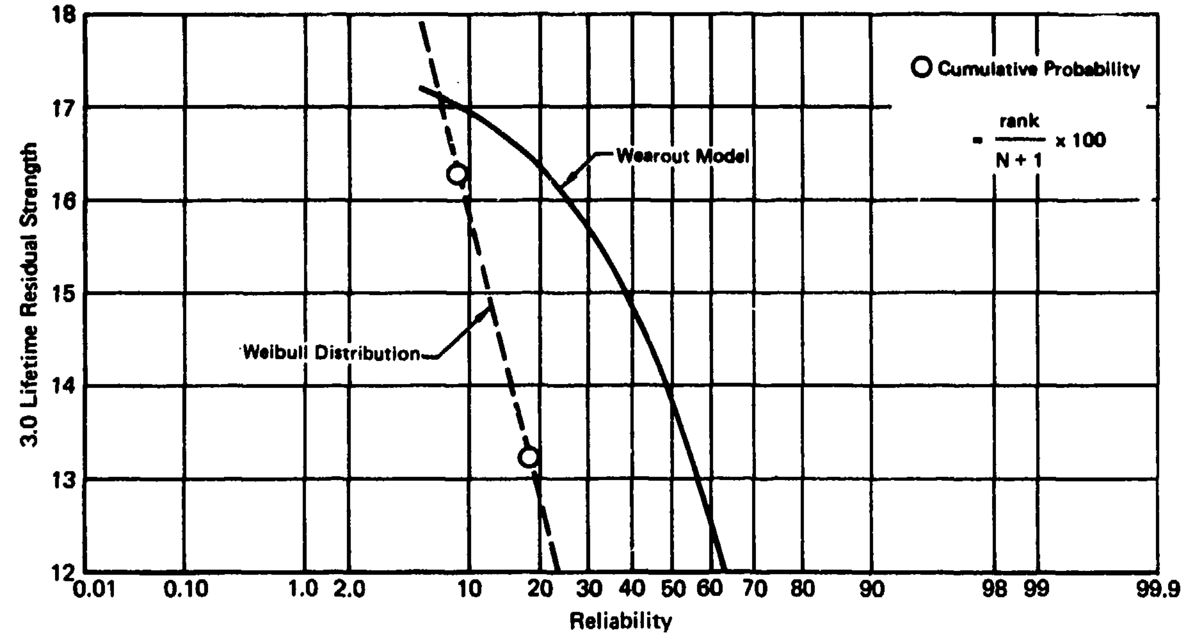

FIGURE 78 COMPARISON OF WEAROUT MODEL FOR SMALL SCALE STEP-LAP SPECIMEN AT 3.0 LIFETIMES WITH WEIBULL DISTRIBUTION

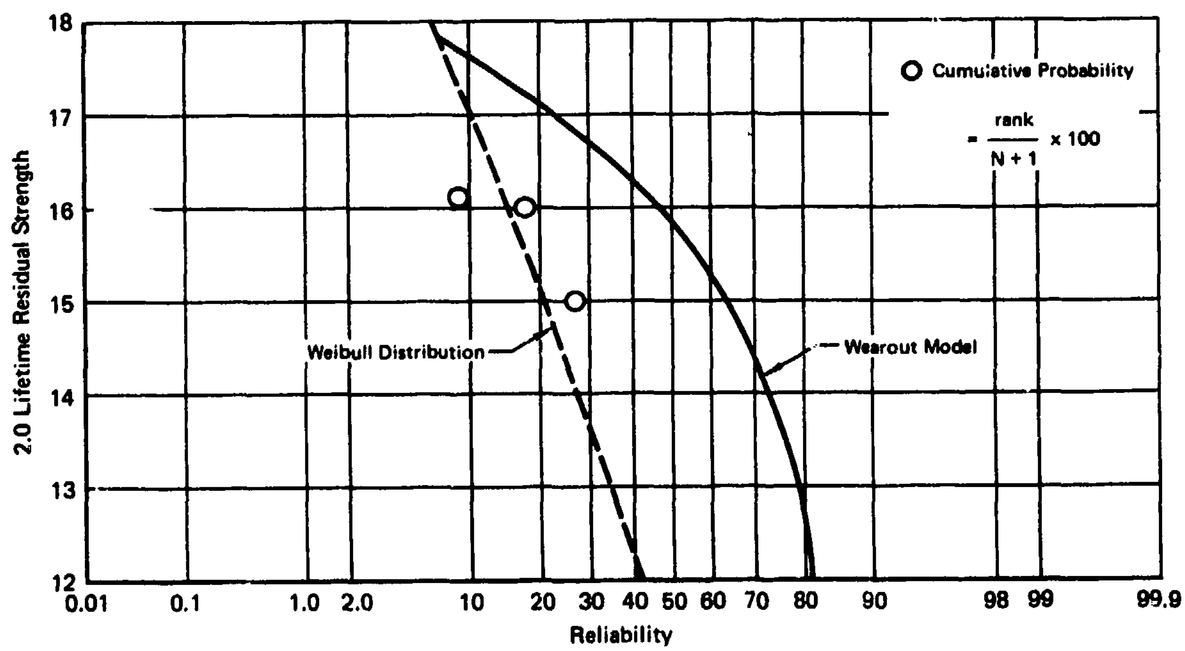

FIGURE 79 COMPARISON OF WEAROUT MODEL FOR SMALL SCALE STEP-LAP SPECIMENS AT 2.0 LIFETIMES WITH WEIBULL DISTRIBUTION

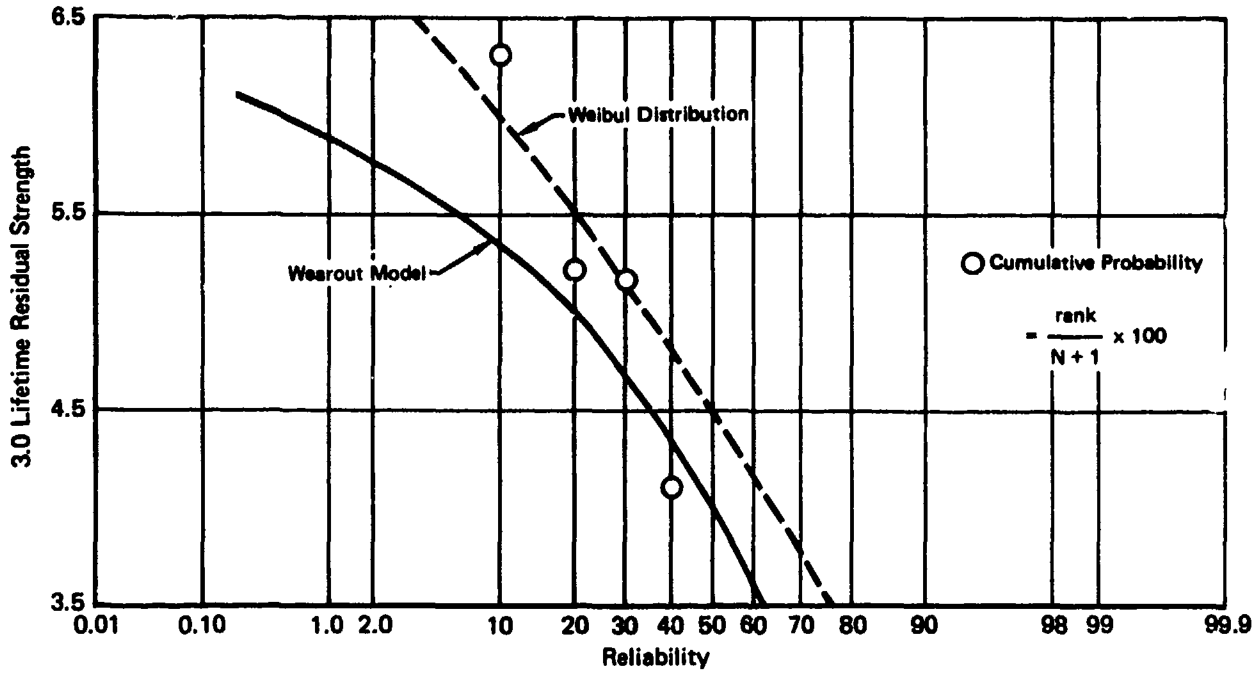

FIGURE 80 COMPARISON OF WEAROUT MODEL FOR SIMPLE SPECIMENS AT 3.0 LIFETIMES WITH WEIBULL DISTRIBUTION

SECTION 7

APPLICATION OF WEAROUT MODEL

In this section the wearout model derived in Section 6 is applied to address the subjects of effects of scale, dependence of Weibull parameters to specimen configuration, the effects of variations in spectrum and environment, proof testing and the inference that can be drawn from the analysis of test results from this program to the design of the F-15 kick splice plate joints.

7.1 Scaling

An evaluation of the scalability of bonded joints was made by comparing the results of the 70% scale step-lap specimen tests with those of the full scale step-lap specimen. It is surmised, based upon this evaluation, that bonded joints are scalable, but that because of practical considerations such as influence of tolerances and determination and control of adhesive thickness, scalability has not been conclusively proven.

It could be concluded that this joint was scaled if the following relations were identically satisfied:

- The shape parameter, α, for 70% scale joint static strength should equal α for the full scale joint: $\alpha_s^{.7} = \alpha_s^{1.0}$.
- The scale parameter, β, for the 70% scale joint static strength should be 70% of the corresponding β for full scale joint: $\beta_s^{.70} = .70\beta_s^{1.0}$.
- And similarly, the shape parameters for fatigue life should be equal:, $\alpha_f^{.70} = \alpha_f^{1.0}$, and the scale parameters for fatigue life should scale:, $\beta_f^{.70} = .70\ \beta_f^{1.0}$ $(TLL^{.70} = .7\ TLL^{1.0})$.

The actual parameter relations from Table 28 are as follows:

$$
\begin{aligned}
\alpha_s^{.70} &= 1.14\ \alpha_s^{1.0} \\
\beta_s^{.70} &= .856\ \beta_s^{1.0} \\
\alpha_f^{.70} &= .878\ \alpha_f^{1.0} \\
\beta_f^{.70} &= .505\ \beta_f^{1.0}\ (TLL^{.70} = .851\ TLL^{1.0})
\end{aligned}
\tag{24}
$$

The actual relationship between $TLL^{.70}$ and $TLL^{1.0}$ is not scaled because the test limit loads were not analytically determined based on an assumption of scalability but that the TLL for each specimen was selected by trial and error to give fatigue failures in the neighborhood of 4.0 lifetimes.

None of the experimental relations are identical to the expected relations. It is thus evident that it cannot be conclusively demonstrated that this joint scales. However, the relations do agree reasonably well considering the effects of tolerances and control of bondline thickness due to adhesive migration into the graphite-epoxy. It is felt that the approximation is close enough to indicate that theoretically joints can be scaled.

7.2 Translation of Parameters

The interest in determining which, if any, of the Weibull parameters of static strength, lifetime and residual strength distributions, translate unchanged from simple adhesive bonded joints to actual joints has been generated by the potential for cost savings (it would be much cheaper to develop shape parameters from simple joints than to use full scale specimens). This program was planned to illustrate if any of the shape parameters from simple specimens would translate unchanged to the full scale step lap specimen. By comparing the shape parameters in Table 28, it can be seen that static and lifetime shape parameters agree reasonably well.

7.3 Effect of Spectrum and Environmental Variations

To determine the effect of spectrum and environmental variations on fatigue life, several full scale step-lap specimens were tested to failure with the baseline spectrum modified in the following ways: 1) added low loads, 2) deleted high loads, 3) frequency of load application reduced to 1/8 of the baseline, and 4) relaxation time between missions increased to ten times the baseline. In addition, several specimens were tested at 350°F to evaluate sensitivity of Weibull parameters to temperature. A comparison of the BLU estimates of the Weibull parameters for baseline spectrum and environment with those for modified spectra and environment is presented in Table 28. The large increase in static shape parameter indicates that less scatter is observed at 350°F. The fatigue shape parameters are affected significantly only by the addition of low load levels and the reduction of the baseline frequency of load applications. In each case, less scatter is indicated. The fatigue scale parameter is reduced for added low load cycles, indicating that the baseline spectrum is unconservative in that

the observed lifetimes under any of the modified spectra would be shorter than indicated by the baseline data, for each modified spectrum. The addition of low loads is the most detrimental. It reduces the fatigue scale parameter to approximately 27 percent of the baseline value. The significant changes in the shape and scale parameters can probably be attributed to the limited number of specimens (3-6 specimens). More data are needed in this area before any definite conclusion can be reached. Indications are that more low load levels should be included in the spectrum when testing adhesive bonded joints than when testing metals. More effort is needed in this area.

7.4 Proof Testing of Bonded Joints

Proof testing has been proposed as a method of improving the reliability of a structure. In this method, each article is preloaded to a level which would reveal unacceptably weak members. For example, if a specific load level is selected for the proof test and the static strength probability distribution at zero time indicates that one percent of the population would fail below that load level, weak members would be eliminated by an initial proof test. Similarly, if the probability distribution at one-half lifetime indicates that ten percent of the population would fail below the proof t[illegible] load level, weak members would be eliminated by a proof test at one-[illegible] lifetime. The weak members eliminated by the proof testing would have be[illegible] among the first articles to fail in fatigue, and therefore the time to first failure would be extended by their elimination.

[illegible]e full scale step-lap specimen used in this program is representative of a conceptual application designed for an ultimate load of 15000 pounds per inch. Design limit load is 10000 pounds per inch. The conceptual application would experience maximum fatigue loads of 12,500 pounds per inch (125% DLL). A likely proof load for such a design would be 12,500 pounds. Proof testing at this level would have detected no weak elements. In fact, only five specimens of all those passing NDT failed at less than 12,500 pounds, and these, after fatigue testing, at 135% of DLL for from 2 to 5.5 lifetimes.

7.5 Implications of Wearout Model on Conceptual Structural Application

To determine what the wearout model implies about the capability of the conceptual structural application it must be recalibrated to reflect a residual strength at a given number of lifetimes equal to the maximum load in the fatigue spectrum (12500 pounds/inch) which is 125 percent of design limit load. The wearout model calibrated in Section 6 applies to a test limit load

(TLL) of 13500 pounds/in. This (TLL) was selected in order to obtain failure in about 4 lifetimes.

To recalibrate the model, values of α_f and β_f are needed for TLL = 10,000 (lbs/in.). To get these values, it is assumed that α_f is independent of load value as indicated in Reference 11. To obtain β_f, a plot of β_f vs TLL is required. In the absence of this data, it is impossible to determine what the probability is for the conceptual application having a certain residual strength at a lower test limit load than the 13500 pounds/inch used for fatigue lift testing.

The wearout model (Figure 76) indicates that the full scale joint has a 75 percent probability of having a residual strength of 16000 lbs/in. after 3 lifetimes of cycling at 135 percent of the design load spectrum. The design limit load (DLL) requirement for the conceptual application is 10,000 pounds/inch. There would be a high probability of having a residual strength of 10,000 pounds/inch after 3 lifetimes.

SECTION 8
COST SUMMARY

In this section a summary of the manhours required to fabricate the specimens, to Non-Destructive Test (NDT) the specimens and to perform the required strength and fatigue life testing is presented. This summary will be useful in estimating cost of fabricating and testing specimens and actual airframe bonded joints similar to those used in this program.

8.1 Specimen Cost

The total time required to fabricate and NDT the simple, small scale step-lap and full scale step-lap specimen is summarized in Table 30. The fabrication cost of each of these specimens is broken down in Tables 31, 32, and 33.

8.2 Test Cost

The estimated cost of running the tests conducted in this program is presented in Table 34.

TABLE 30
SUMMARY OF SPECIMEN COSTS

Specimen Identification	Materials(1) Costs	NDT Costs (mhrs)	Fabrication(2) Costs (mhrs)
Simple Specimen	$1.30	0.80	1.39
Small Scale Step-Lap	$7.75	1.40	5.46
Full Scale Step-Lap	$22.10	1.40	5.60

(1) Allowing 20% for scrappage
(2) Spreading set-up costs over total number of specimen fabricated

TABLE 31 SIMPLE SPECIMEN FABRICATION COST BREAKDOWN

Operation Number	Operation	Cost in Hrs. for First 10	Cost in Hrs. for Additional 10
1	Engineering liason, and engineering effort required to establish design, fabrication and machining procedures for making a simple joint panel assembly to provide 10 simple joint test specimens.	5.0	0.0
2	Chem-Mill titanium sheet stock to required thickness.	4.0	0.0
3	Conventionally machine titanium into details required to fabricate a simple joint panel assembly.	4.0	1.0 (2)
4	Fabricate aluminum dams and cover plates required to fabricate the simple joint panel assembly.	0.5	0.5
5	Lay-up the graphite/epoxy and MMS-307 Type I film adhesive assemblies required to fabricate the simple joint panel assemblies.	2.0	0.5
6	Clean and prime titanium details from Operation No. 3.	2.0	0.5
7	Assemble the simple joint panel assembly and the required layup configuration.	2.0	1.0
8	Cure the simple joint panel assembly.	4.0	0.0
9	Remove the simple joint panel assembly from the layup configuration.	1.0	0.5
10	Post-cure the simple joint panel assembly.	0.5	0.0
11	Machine the simple joint panel assembly into simple joint test specimens using a diamond cut-off wheel.	6.0	6.0
12	Remove titanium spacer details from the simple joint test specimens and clean up and identify the test specimens.	1.5	1.5
	Totals	32.5	11.5

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Notes:

1. Cost breakdown is based upon fabricating a simple joint panel assembly which provides 10 simple joint test specimens.
2. Cost breakdown is based upon stacking two pieces of titanium sheet stock and machining both pieces to the required lengths and widths simultaneously.
3. The cost in hours for additional test specimens (in 10 specimen increments) is generally applicable up to a total quantity of approximately 50 test specimens. For quantities of specimens greater than 50, e.g., 100, the cost in hours noted for the first 10 specimens should be multiplied by 2 and the cost in hours noted for additional 10 specimens should be multiplied by 8. If the quantity of specimens are to be fabricated at various times to simulate production runs the cost in hours noted for the first 10 specimens for Operation Nos 5 through 10 should be included as many times as the required number of simulated production runs.

TABLE 32 SMALL SCALE STEP-LAP SPECIMEN FABRICATION COST BREAKDOWN

Operation Number	Operation	Cost in Hrs. for First 10	Cost in Hrs. for Additional 10
1	Engineering liason, and engineering effort required to establish design, fabrication and machining procedures for making a small step-lap panel assembly which provides 10 small step-lap test specimens.	24.0	0.0
2	Rough saw two pieces of titanium from ½ inch thick stock.	3.0	3.0
3	Machine two pieces of titanium to required thickness holding required flatness and parallelism.	4.0	4.0
4	Machine two pieces of titanium to required width and length.	4.0	1.0 (3)
5	Machine initial step into each side of each piece of titanium.	3.0	3.0
6	Drill tooling holes in one titanium detail.	0.5	0.0
7	Fabricate one Chem-Mill template using titanium detail from Operation No. 6.	8.0	8.0
8	Drill tooling holes in remaining titanium detail using template from Operation No. 7.	0.3	0.3
9	Chem-Mill remaining steps into each side of each piece of titanium using template from Operation No. 7.	8.0	8.0
10	Machine Chem-Milled titanium to required length.	1.0	1.0
11	Fabricate aluminum cover plates required to fabricate the panel assembly.	0.2	0.2
12	Layup 13 graphite/epoxy laminates (1 configuration for each step on each side and 1 configuration for the land area between the titanium) required to fabricate the panel assembly.	6.0	1.5
13	Clean and prime the titanium details from Operation No. 10.	2.0	0.5
14	Install titanium details in assembly fixture.	0.3	0.3
15	Cut MMS-307 Type I film adhesive strips and apply to both sides of each titanium detail. Install graphite/Epoxy laminate in the land area between the titanium and cover the strips of MMS-307 Type I film adhesive	1.5	1.5
16	Assemble the 12 remaining graphite/epoxy laminates from Operation No. 12 into the required panel assembly configuration.	2.0	2.0
17	Place the completed panel assembly into the required layup configuration.	2.0	2.0
18	Cure the panel assembly.	4.0	4.0
19	Remove the panel assembly from the layup configuration.	1.5	0.5
20	Post-cure the panel assembly.	0.5	0.0
21	Machine the panel assembly into test specimens	16.0	16.0
22	Cleanup and identify test specimens.	1.5	1.5
	Total	93.3	50.3

Notes:

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1. Cost breakdown is based upon fabricating a small step-lap panel assembly which provides 10 small test specimens
2. Cost breakdown does not include 12 hours required to design the required assembly fixture nor does it include the 48 hours required to fabricate two such fixtures. The fixture was designed to accommodate both the small and intermediate step-lap panel assemblies so that the cost could be spread out over the entire step-lap panel assembly fabrication
3. Cost breakdown is based upon stacking 4 pieces of titanium and machining all pieces simultaneously
4. The cost breakdown is generally applicable up to a total quantity of 20 specimens in that only two assembly fixtures were fabricated. However, in estimating for quantities of specimens greater than 20, the cost in hours noted for the first 10 specimens for Operation Nos. 1, 6, 7 and 11 should be deleted and the cost in hours noted for additional 10 specimens for Operation No. 11 should be deleted
5. Operation Nos. 6, 7, 8, 9 and 10 may be deleted and replaced by an operation involving the conventional machining of the required number of steps into the titanium details especially when only a limited number of test specimens are to be fabricated

TABLE 33 FULL SCALE STEP-LAP SPECIMEN FABRICATION COST BREAKDOWN

Operation Number	Operation	Cost in Hrs for First 10	Cost in Hrs for Additional 10
1	Engineering liaison, and engineering effort required to establish design, fabrication and machining procedures for making an intermediate step-lap panel assembly which provides 10 intermediate steo-lap test specimens.	24.0	0.0
2	Rough saw two pieces of titanium from 1/2 inch thick stock.	3.5	3.5
3	Machine two pieces of titanium to required thickness holding required flatness and parallelism.	5.0	5.0
4	Machine two pieces of titanium to required width and length.	4.5	1.5 (1)
5	Machine initial step into each side of each piece of titanium.	3.5	3.5
6	Drill tooling holes in one titanium detail.	0.5	0.0
7	Fabricate one chem-mill template using titanium detail from Operation Number 6.	8.0	8.0
8	Drill Tooling Holes in Remaining Titanium Detail Using Template From Operation Number 7	0.3	0.3
9	Chem-Mill Remaining Steps Into Each Side of Each Piece of Titanium Using Template from Operation Number 7	8.0	2.0
10	Machine chem-milled titanium to required length.	1.0	1.0
11	Fabricate aluminum cover plates required to fabricate the panel assembly.	0.2	0.2
12	Layup 13 graphite/epoxy laminates (1 configuration for each step on each step on each side and 1 configuration for the land area between the titanium) required to fabricate the panel assembly.	6.0	1.5
13	Clean and prime the titanium details from Operation Number 10.	2.0	0.5
14	Install titanium details in assembly fixture.	0.3	0.3
15	Cut MMS-307 Type I film adhesive strips and apply to both sides of each titanium detail. Install graphite/epoxy laminate in the land area between the titanium and cover with strips of MMS-307 Type I film adhesive.	1.5	1.5
16	Assemble the 12 Remaining Graphite/Epoxy Laminates from Operation Number 12 into the Required Panel Assembly Configuration	2.0	2.0
17	Place the completed panel assembly into the required layup configuration.	2.0	2.0
18	Cure the Panel Assembly	4.0	0.0
19	Remove the panel assembly from the layup configuration.	1.5	0.5
20	Post-cure the panel assembly	0.5	0.0
21	Machine the panel assembly into test specimens	18.0	18.0
22	Cleanup and identify test specimens.	1.5	1.5
	Totals	97.8	50.8

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Notes:

1. Cost breakdown is based upon fabricating an intermediate step-lap panel assembly which provides 10 intermediate step-lap test specimens
2. See note 2 for small step-lap cost breakdown
3. See note 3 for small step-lap cost breakdown
4. See notes 4 and 5 for small step-lap cost breakdown

TABLE 34 ESTIMATED COST TO CONDUCT TESTS

Type Test	Spectrum Description	Temperature	Set Up Time (Manhours)	Test Time per 1000 Spectrum Hrs (Manhours)	Test Time (Manhours)
Static	N/A	R.T.	1	0	0.50
Static	N/A	350°F	1	0	0.75
Fatigue	Baseline	R.T.	0	0.42	0
Fatigue	Baseline	350°F	0	0.42	0
Fatigue	Low Loads Included	R.T.	0	3.32	0
Fatigue	High Loads Excluded	R.T.	0	0.42	0
Fatigue	1/8 Baseline Frequency	R.T.	0	3.36	0
Fatigue	10 Times Baseline Relaxation	R.T.	0	2.22	0

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SECTION 9

CONCLUSIONS AND RECOMMENDATIONS

The "Reliability of Step-Lap Bonded Joints" program has demonstrated that the wearout model derived in Appendix B can be successfully used to predict the residual strength characteristics of adhesive bonded joints under a given spectrum and environment. The fatigue spectrum utilized represented fighter aircraft flight by flight loading and was developed using random noise theory and actual fighter and attack training data to establish appropriate PSD shapes for fighter aircraft maneuvering time histories. Indications are that the exclusion of low load levels from the spectrum and the use of short relaxation times between missions may lead to unconservative estimates of fatigue life. However, this observation is based on very few data points and additional testing is required to verify these trends. The program has shown that certain Weibull parameters used in the development of a wearout model of a full scale adhesive bonded joint, namely α_s, can be reasonably approximated by the same parameter developed for simple specimens which fail in similar modes. It was shown that the design procedures used for the conceptual structural application, produced a highly reliable structure. Finally, it was illustrated that although bonded joints can be theoretically scaled the problem of obtaining scaled adhesives, and controlling tolerances, makes scaling impractical and not economically justified in most cases.

Based upon the results of the "Reliability of Step-Lap Bonded Joints" program the following reccommendations are made:

(1) Further work should be done to study the effect of spectrum variations, especially the exclusion of low load levels and the use of short relaxation times, on the fatigue life of adhesive bonded joints and that the wearout model be used in the study.

(2) A study should be conducted to determine what uncontrolled variables lead to the batch effects in the fabrication of graphite-epoxy-to-titanium bonded joints.

(3) The elastic-plastic analysis procedure for adhesive bonded joints along with available adhesive shear stress strain curves should be included in the "Structural Design Guide for Advanced Composite Application."

(4) Further work should be conducted to determine moisture effects on graphite-epoxy-to-titanium bonded joints.

(5) Further work should be conducted to establish NDT acceptance criteria for wide graphite-epoxy to titanium splice-plates such as those found in representative aircraft structure.

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APPENDIX A
COMPUTER PROGRAM A4EGX

A.1 A4EGX Input Data Required

The computer program A4EGX computes the elastic and elastic-plastic joint strength of any step-lap bonded joint. The program prints out the most critical adherend and adhesive stresses for each step of the joint. The input data is printed out to supplement the solution output. The program accounts for arbitrary combinations of adherend stiffnesses, thermal imbalances, non-uniform step thickness increments, and non-uniform step lengths.

The input data required is read in by three card sets.

CARD SET 1: (Format I2 - One Card)

Number of joint configurations user desires to solve (card sets 2 & 3 must be input for each configuration)

CARD SET 2: (Format 8F10.3 - 2 Cards)

TAUMAX	∿	Peak Adhesive Shear Stress (τ_p)
G	∿	Elastic Adhesive Shear Modulus
GAMMAX	∿	Maximum Adhesive Shear Strain ($\gamma_e + \gamma_p$)
GAMMAE	∿	Elastic Adhesive Shear Strain (must exactly equal τ_p/G)
ETA	∿	Bond Line Thickness (η)
ALPHAO	∿	Outer Adherend Coefficient of Thermal Expansion (α_o)
ALPHA1	∿	Inner Adherend Coefficient of Thermal Expansion (α_i)
DELTEMP	∿	Temperature Differential ($T_{operating} - T_{stress\ free}$)
SGNLD	∿	+1. For Tension Joint Loading -1. For Compression Joint Loading
ANSTEP	∿	Number of Steps in the Joint (controls number of cards required in card set 3)

CARD SET 3: (Format 7F10.3 - Number of Cards Required is *N = ANSTEP + 1)

THICKO (N)	∿	Sum of Outer Adherend Thicknesses (In)
THICK1 (N)	∿	Thickness of Inner Adherend (In)
STEPL (N)	∿	Length of Nth Step (In)
ETOTR (N)	∿	Net Extensional Stiffness of Outer Adherend ($E_o t_o$) at Nth Step
ETINR (N)	∿	Extensional Stiffness of Inner Adherend ($E_i t_i$) at Nth Step

STROTR (N) $\sim$ Net Strength of Outer Adherends (Lb/In) at Nth Step

STRINR (N) $\sim$ Strength of Inner Adherend (Lb/In) at Nth Step

* The last step required is actually the portion of the joint just after the final step terminates. (Ref. Figure A-1)

Thus at the last step:

THICKO (N) = 0.	THICKI (N) = THICKI (N-1)
STEPL (N) = 0.	ETINR (N) = ETINR (N-1)
ETOTR (N) = 0.	STRINR (N) = STRINR (N-1)
STROTR (N) = 0.	

The card set formats listed above are for use on the IBM 370/195.

The data given on card set 2 needs further elaboration. The data needed to typify the adhesive system is obtained by modeling the actual adhesive stress-strain curve, obtained from torsion ring or thick adherend testing if available, into an elastic-plastic curve.

Consider the following ductile adhesive stress-strain curve, Figure A-2, at room temperature and the idealized elastic-plastic equivalent. The variables needed for card set 2 are defined by this figure.

A.2 Stepped-Lap Joint Parametric Trends

Using the A4EGX analytic procedure certain parametric trends become evident with respect to adhesive bonded step-lap joints. The following characteristics should be acknowledged and accounted for in both the design and analysis of an optimized step-lap joint configuration.

a. Each step is loaded via a lightly loaded elastic trough with high elastic spikes developing at the step-to-step interfaces. At the final step(s) of the joining plastic "plateaus" may develop instead of the elastic spikes.

b. The ductility of the adhesive system plays the dominate role in suppressing the elastic spikes, increasing the average adhesive shear stress per step, and promoting formation of the plastic "plateau" regions.

c. On any one step, beyond a certain overlap length, no additional gains in load carrying capacity are achieved. To acquire more load capacity more steps of reduced step thickness are required.

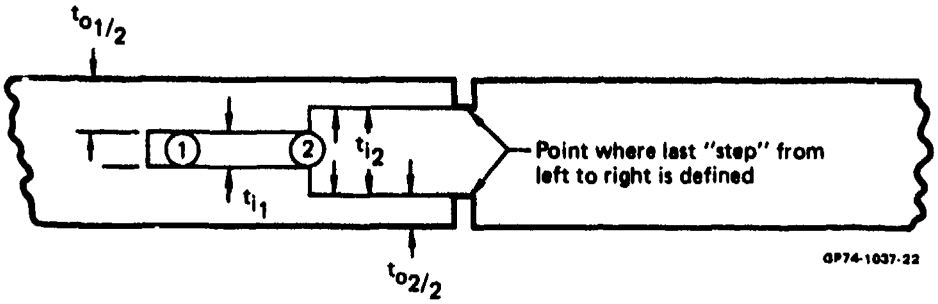

FIGURE A-1 TWO STEP JOINT

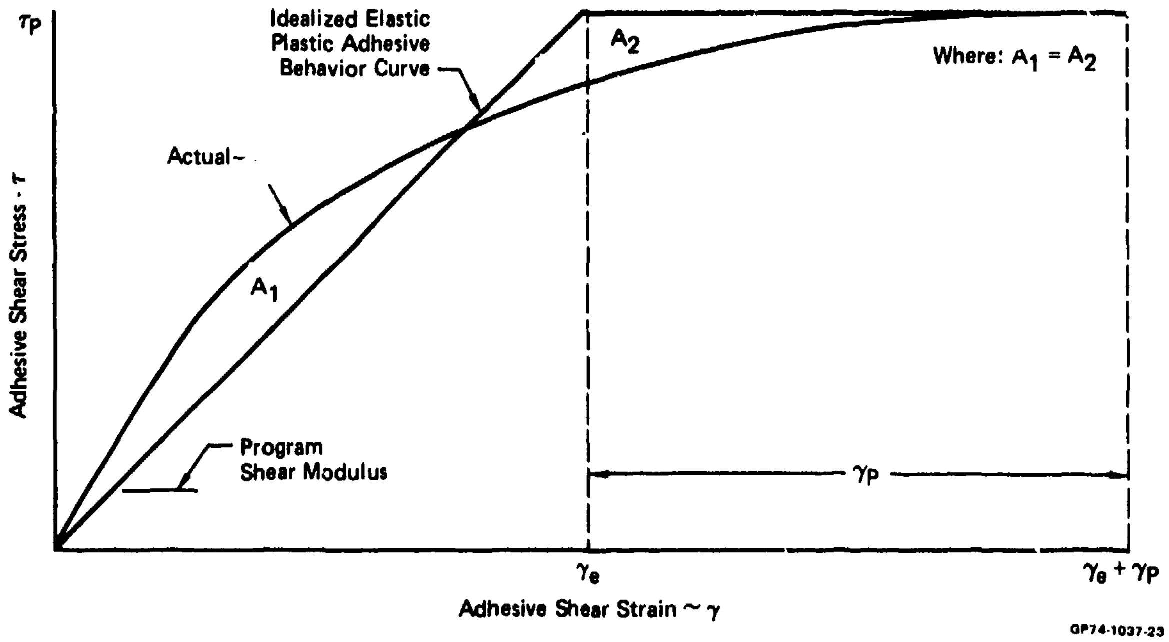

FIGURE A-2 TYPICAL ADHESIVE STRESS-STRAIN CURVE

d. Adherend stiffness imbalance always effects a reduction in joint efficiency. The end of the joint from which the less stiff adherend extends will have intensified shear strains, thus the imbalance reduces strength by unloading the less critical end.

e. Adherend thermal mismatch may cause the critical end of a step lap joint to change ends when the load is reversed. This step-lap joint characteristic requires analyses to be performed with the maximum tensile and maximum compression loads to determine the limiting joint strength capability.

f. In a reasonably well designed step-lap joint, the joint load capacity is basically determined by the end three steps of the more critical end of the joint. In fact, once a joint is fairly well optimized major changes to steps other than the first three will cause very little change in overall joint capability. The reality of this type of internal stress distribution in step lap joints dictates that the average adhesive shear stress, in the critical end's first three steps, will in reality be considerably higher than the average adhesive shear stress of the overall joint or of any remaining joint step.

A.3 Program Listing

The program listing follows:

```
.080 @AD
.090 @FIXED
.100 CDECK A4EG
.110 C STEPPED-LAP ADHESIVE-BONDED-JOINTS
.120 C ELASTIC-PLASTIC SOLUTIONS
.130 C JOINT ANALYSIS PROGRAM
.140 C SOLUTION EXAMINES ADHESIVE SHEAR STRESS AND ADHEREND NORMAL (AXIAL)
.150 C      1  STRESS BUT OMITS CONSIDERATION OF ADHESIVE PEEL STRESS ON THE
.160 C      2  GROUND THAT OUTER END STEP IS USUALLY SUFFICIENTLY THIN FOR
.170 C      3  PEEL STRESS PROBLEMS NOT TO ARISE
.180 C NOTE THAT CONVERGENCE PROBLEM IS ACUTE FOR STEPPED-LAP JOINTS, EVEN
.190 C      1  WITH DOUBLE-PRECISION.  STEPS TAKEN HERE TO CONSTRAIN TENDENCY
.200 C      2  TO DIVERGE (BY FREEZING SOLUTION ONE STEP AT A TIME) HAVE BEEN
.210 C      3  ADOPTED AFTER TRYING BOTH MORE AND LESS STRINGENT TECHNIQUES
.220 C NOTE ALSO THAT CONVERGENCE DIFFICULTIES ARE PROBLEM DEPENDENT, BEING
.230 C      1  MORE SEVERE FOR BRITTLE (HIGH MODULUS) ADHESIVES.  LOW MODULUS
.240 C      2  ADHESIVES PROVED AMENABLE TO A CONVERGENT SOLUTION IN ONLY A
.250 C      3  SINGLE PASS STRAIGHT THROUGH THE JOINT FROM END TO END, IN
.260 C      4  SINGLE-PRECISION, WITH ONLY A SMALL LOSS OF ACCURACY IN LATER
.270 C      5  STEPS.
.280 C THE UNDERLYING DIFFICULTY IS ONE OF NUMERICAL ACCURACY LOSS IN THE
.290 C      1  PRESENCE OF EXTREMELY HIGH ADHESIVE SHEAR STRESS GRADIENTS AT
.300 C      2  BOTH ENDS OF EACH OF THE OUTER STEPS.
.310       DIMENSION TOUTER(150), TINNER(150), GAMMA(150), TAU(150),
.320      1  DELTAO(150), DELTAI(150), STEPL(50), THICKO(50), THICKI(50),
.330      2  ETOTR(50), ETINR(50), STROTR(50), STRINR(50), STEP(150),
.340      3  THCKNO(150), THCKNI(150), ETOUTR(150), ETINNR(150), STRGTR(150),
.350      4  STRGNR(150)
.360       DOUBLE PRECISION TOUTER, TINNER, GAMMA, TAU, DELTAO, DELTAI,
.370      1  TMAX, TMIN, A, B, C, D, E, F, ALAMDA, DELT, DELDLT, C1, C2, C3,
.380      2  C4, C5,     C7, V, V4, V5, V6, V7, V8, V9, V10, STEP, TCHECK,
.390      3  THCKNO, THCKNI, ETOUTR, ETINNR, STRGTR, STRGNR, STEPL, THICKO,
.400      4  THICKI, ETOTR, ETINR, STROTR, STRINR, TAUUPR, TAULWR, GAMUPR,
.410      5  GAMLWR, ELSTR, XP, EL, ELMAX, ELMIN,          C10
.412       CALL OPENFB ('DATA2 ',1)
.414        READ(5,), IOOO
.420        READ(5,),    M
.430 C M .EQ. NUMBER OF JOINT CONFIGURATIONS TO BE SOLVED
.440 C READ IN MATERIAL PROPERTIES
.450       DO 820 MCOUNT = 1, M
.460       NRVRS = 0
.470       JFLAG = 1
.480 C JFLAG IDENTIFIES END OF JOINT FROM WHICH ANALYSIS COMMENCES
.490       READ(5,),     TAUMAX, G, GAMMAX, GAMMAE, ETA, ALPHAO, ALPHAI,
.500      1     DELTMP, SGNLD, ANSTEP
.510       NSTEPS = ANSTEP
.520       MSTEPS = NSTEPS + 1
.530       LMAX = 3 * NSTEPS
.540       MCHECK = LMAX + 1
.550 C READ IN JOINT GEOMETRY
.560       READ(5,),     ((THICKO(N), THICKI(N), STEPL(N), ETOTR(N), ETINR(N),
.570      1     STROTR(N), STRINR(N)), N = 1, MSTEPS)
.580 C CHECK ON CONSISTENCY OF ADHESIVE DATA
.590       VCHECK = G * GAMMAE
.600       R = TAUMAX / VCHECK
.610       IF ((1.001 .LT. R) .OR. (0.999 .GT. R)) GO TO 820
.620       IF (GAMMAX .GE. GAMMAE) GO TO 40
.630 C IF NOT, REDUCE PEAK SHEAR STRESS TO LESS THAN MAXIMUM ELASTIC VALUE
.640       TAUMAX = G * GAMMAX
.650       GAMMAE = GAMMAX
```

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```
C CHECK ON ADHEREND THICKNESSES AT EACH STEP
C SUM LAP LENGTHS
   40 VCHCK1 = THICKI(1) + THICKO(1)
      OLAP = STEPL(1)
      DO 50 N = 2, NSTEPS
      OLAP = OLAP + STEPL(N)
      VCHCK2 = THICKI(N) + THICKO(N)
      R = VCHCK1 / VCHCK2
C     IF ((1.001 .LT. R) .OR. (0.999 .GT. R)) GO TO 820
   50 CONTINUE
C SET UP RECURRING CONSTANTS
      C1 = G / ETA
      C2 = 2. * C1
C FACTOR 2. ACCOUNTS FOR BONDING ON BOTH SIDES OF "INNER" ADHEREND.
C     1  IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
      C7 = -1. + GAMMAE
      C10 = -1. * TAUMAX
   60 C3 = ALPHAO * DELTMP
      C4 = ALPHAI * DELTMP
      C5 = C4 - C3
C
C PREPARE FOR SEPARATE COMPUTATION OF POTENTIAL ADHESIVE SHEAR STRENGTH
C     1  ON ASSUMPTION OF ACTUAL ADHEREND STIFFNESSES & INFINITE STRENGTH
      KADHSV = 0
C
C PRINT OUT INPUT DATA
   70 WRITE (IOOO,80) ALPHAO, ALPHAI, DELTMP
   80 FORMAT (1H1/, 5(1H0/), 11H INPUT DATA//, 10H ALPHAO = , F10.7,
     1  13H (PER DEG. F), 3X, 9HALPHAI = , F10.7, 13H (PER DEG. F)/,
     225X, 9HDELTMP = , F6.1, 9H (DEG. F)//,
     3  1H , 5X, 1HN, 2X, 5HSTEPL, 1X, 6HTHICKO, 1X, 6HTHICKI, 4X,
     4  6HSTROTR, 5X, 6HSTRINR, 5X, 5HETOTR, 5X, 5HETINR//)
      DO 100 N = 1, MSTEPS
      WRITE (IOOO,90) N, STEPL(N), THICKO(N), THICKI(N), STROTR(N),
     1 STRINR(N), ETOTR(N), ETINR(N)
   90 FORMAT (1H , 4X, I2, 3(1X, F6.4), 2(1X, F10.1), 2(1X, F10.1))
  100 CONTINUE
      IF (KADHSV.EQ. 1) GO TO 410
C
C START WITH ELASTIC ANALYSIS
C PROCEED TO ELASTIC-PLASTIC ANALYSIS ONLY IF ADHESIVE IS MORE CRITICAL
C     1  THAN ADHEREND(S)
C NEED ELASTIC SOLUTION TO IDENTIFY CRITICAL END FOR ELASTIC-PLASTIC
C     1  SOLUTION WHEN BOTH THERMAL AND STIFFNESS ADHEREND MISMATCHES
C     2  ARE PRESENT
C ESTIMATE MAXIMUM POSSIBLE BOND CAPACITY FOR FULLY-PLASTIC ADHESIVE
      PBOND = TAUMAX * OLAP * 2.
C NOTE FACTOR 2. INCLUDED FOR DOUBLE-SIDED JOINT
C REDUCE TO 1. IF JOINT HAS ONLY ONE SIDE BONDED
C PERFECTLY-ELASTIC BOND CAPACITY WILL BE CLOSER TO ASYMPTOTE OF SCARF
C     1  JOINT SOLUTION AND IS SIGNIFICANTLY LOWER THAN PLASTIC ESTIMATE
C ESTIMATE APPROXIMATE ELASTIC LOAD CAPACITY FROM SCARF JOINT SOLUTION
C     V1 = ETOTR(1) / ETINR(MSTEPS)
C     V2 = ETINR(MSTEPS) / ETOTR(1)
C     IF (V1 .GE. 1.) PBOND = TAUMAX * OLAP * V2 * 2.
C     IF (V2 .GE. 1.) PBOND = TAUMAX * OLAP * V1 * 2.
C NOTE FACTOR 2. INCLUDED FOR DOUBLE-SIDED JOINT
C REDUCE TO 1. IF JOINT HAS ONLY ONE SIDE BONDED
C ACTUAL LOAD CAPACITY MAY BE SIGNIFICANTLY LESS IF THERMAL MISMATCH
C     1  BETWEEN ADHERENDS IS SEVERE
C REDUCTION IN LOAD TO ACCOUNT FOR LIMITED ADHEREND STRENGTH IS
```

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```
C     1  ACCOMPLISHED LATER IN PROGRAM
C PROVIDE OUTER LOOP TO ADJUST ADHESIVE PEAK SHEAR STRAIN AT START OF
C     1  JOINT FOR CASES IN WHICH EITHER ADHESIVE IS MORE CRITICAL AT
C     2  OTHER END OF JOINT OR ADHERENDS ARE MORE CRITICAL THAN ADHESIVE.
         TAUUPR = 2. * TAUMAX
         TAULWR = 0.
C NOTE THAT PROGRAM IS PREVENTED FROM HANDLING PROBLEM IN WHICH SHEAR
C     1  STRESS IN ADHESIVE REVERSES SIGN, WHEN COMPUTATIONS START FROM
C     2  THE LESS CRITICAL END.  SOLUTION IS OBTAINABLE FROM OTHER END.
C NOTE ALSO THAT, IF THE MAXIMUM SHEAR STRESS AND APPLIED LOADS HAVE
C     1  OPPOSITE SIGNS, JOINT MUST BREAK APART UNDER RESIDUAL THERMAL
C     2  STRESS ALONE WITHOUT ANY EXTERNALLY APPLIED LOAD, SO NO CASES OF
C     3  REAL CONCERN ARE EXCLUDED BY THE RESTRICTION ABOVE
         DO 310 I = 1, 50
         TAU(1) = (TAUUPR + TAULWR) / 2.
         IF (TAU(1) .GT. TAUMAX) TAU(1) = TAUMAX
         IF (I .EQ. 1) TAU(1) = TAUMAX
C SET INITIAL CONDITIONS
         GAMMA(1) = TAU(1) / G
         TOUTER(1) = 5. * PCOND
         TINNER(1) = 0.
         DELTAO(1) = 0.
         DELTAI(1) = SGNLD * GAMMA(1) * ETA
         TMAX = 10. * PCOND
         TMIN = 0.
C OPERATE ON THE LOAD LEVEL IN INTERMEDIATE LOOP
C LEAVE ADJUSTMENT OF TAUMAX FOR OUTER LOOP
         TCHECK = 0.
         DO 210 IFLAG = 1, NSTEPS
         SCHECK = 1000000000000000.
         DO 170 NCOUNT = 1, 100
C CONVERGENCE NEARLY ALWAYS OCCURRED BETWEEN 20 AND 30 CYCLES IN TEST
C     1  CASES, BUT THERE WERE SOME EXCEPTIONS
C INTERMEDIATE LOOP ADJUSTS LOAD LEVEL
         V10 = -1. * TOUTER(1)
C CHECK ON CONVERGENCE OF TOUTER(IFLAG)
         R = TOUTER(IFLAG) / SCHECK
         IF ( (1.000000001 .GT. R) .AND. (0.999999999 .LT. R) ) GO TO 180
         DO 120 N = IFLAG, NSTEPS
C INNER LOOP COMPUTES ELASTIC JOINT STRENGTH
         A = TAU(N)
         ALAMDA = DSQRT(C2 * (1. / ETINR(N) + 1. / ETOTR(N)))
         B = (TINNER(N) / ETINR(N) - TOUTER(N) / ETOTR(N) + C5 * SGNLD)
        1  * C1 / ALAMDA
C NOTE THAT SGNLD SIGNIFIES WHETHER SHEAR LOAD IS TENSILE OR COMPRESSIVE
         C = STEPL(N)
         D = ALAMDA * C
         E = DSINH(D)
         F = DCOSH(D)
         TAU(N+1) = A * F + B * E
         DELT = (2. / ALAMDA) * (A * E + B * (F - 1.))
C FACTOR 2. ACCOUNTS FOR BONDING ON BOTH SIDES OF 'INNER' ADHEREND.
C     1  IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
         TOUTER(N+1) = TOUTER(N) - DELT
         TINNER(N+1) = TINNER(N) + DELT
         IF (N .EQ. NSTEPS) GO TO 110
         IF (TAU(N+1) .LT. C10) GO TO 150
         IF (TOUTER(N+1) .LT. V10) GO TO 160
C NOTE THAT THESE CONVERGENCE CHECKS ARE CRITICAL
C IF THE FACTOR =1. IS TOO LARGE OR TOO SMALL, CONVERGENCE FAILS
 110     DELDLT = (2. / (ALAMDA**2)) * (A * (F - 1.) + B * (E - D))
```

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```
C FACTOR 2. ACCOUNTS FOR BONDING ON BOTH SIDES OF "INNER" ADHEREND.
C    1  IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
      DELTAO(N+1) = DELTAO(N) + C3 * C + SGNLD * (TOUTER(N) * C -
     1  DELDLT) / ETOTR(N)
      DELTAI(N+1) = DELTAI(N) + C4 * C + SGNLD * (TINNER(N) * C +
     1  DELDLT) / ETINR(N)
      GAMMA(N+1) = TAU(N+1) / G
  120 CONTINUE
C CHECK WHETHER OR NOT PRECISELY 100 PERCENT OF LOAD HAS TRANSFERRED
      R1 = TOUTER(1) / TINNER(MSTEPS)
C CHECK ALSO WHETHER OR NOT CONVERGENCE HAS BEEN OBTAINED
      R2 = TCHECK / TINNER(MSTEPS)
      IF ( (1.000001 .GT. R1) .AND. (0.999999 .LT. R1) .AND.
     1  (1.000001 .GT. R2) .AND. (0.999999 .LT. R2) ) GO TO 220
      IF (TOUTER(1) .LT. TINNER(MSTEPS)) GO TO 130
C IF SO, LOAD ESTIMATE IS TOO LOW
C IF NOT, LOAD ESTIMATE IS TOO HIGH
      GO TO 140
C R1 IS UNSUITABLE FOR A CONVERGENCE CHECK BECAUSE NEGATIVE VALUES OF R1
C    1  REPRESENT TOO HIGH A LOAD ESTIMATE, JUST LIKE THOSE VALUES IN
C    2  EXCESS OF UNITY
  130 TMIN = TOUTER(IFLAG)
      TOUTER(IFLAG) = (TMIN + TMAX) / 2.
      TCHECK = TINNER(MSTEPS)
      GO TO 170
  140 TMAX = TOUTER(IFLAG)
      TOUTER(IFLAG) = (TMIN + TMAX) / 2.
      TCHECK = TINNER(MSTEPS)
      GO TO 170
C NOTE THAT LABELS 26 AND 7 GOVERN FINE ADJUSTMENTS TO THE JOINT LOADS,
C    1  WHILE LABELS 27 AND 28 REPRESENT COARSE ADJUSTMENTS
  150 TMAX = TOUTER(IFLAG)
      SCHECK = TOUTER(IFLAG)
      TOUTER(IFLAG) = (TMIN + TMAX) / 2.
      GO TO 170
  160 TMIN = TOUTER(IFLAG)
      SCHECK = TOUTER(IFLAG)
C IF ADHEREND, RATHER THAN ADHESIVE, LIMITS JOINT STRENGTH, NEED TO
C    1  BOOST PLOAD IN PROPORTION TO TAUMAX, EVEN IF IT MEANS EXCEEDING
C    2  ADHEREND STRENGTHS IN INTERMEDIATE COMPUTATIONS.  CORRECTIONS
C    3  ARE APPLIED LATER
      IF (TMIN .GE. TMAX) TMAX = 5. * TMAX
      TOUTER(IFLAG) = (TMIN + TMAX) / 2.
  170 CONTINUE
      IF (N .EQ. NSTEPS) GO TO 210
C CONVERGENCE WILL NOT PROCEED TO FAR END OF JOINT IN SINGLE PASS
C    1  BECAUSE OF NUMERICAL ACCURACY PROBLEMS.  REMEDY IS TO FREEZE
C    2  EARLIER VALUES, WHICH HAVE CONVERGED AND SLIGHTLY PERTURB
C    3  INTERMEDIATE VALUES, AND TO CHECK FOR CONVERGENCE AT THE FAR END
      TMAX = TOUTER(1)
      TMIN = -1. * TMAX
      GO TO 210
  180 ICOUNT = IFLAG + 1
      IF (TOUTER(ICOUNT) .GT. 0.) GO TO 190
      IF (TOUTER(ICOUNT) .LT. 0.) GO TO 200
      TMAX = TOUTER(1) / 10.
      TMIN = -1. * TMAX
      GO TO 210
  190 TMAX = 1.1 * TOUTER(ICOUNT)
      TMIN = 0.9 * TOUTER(ICOUNT)
      GO TO 210
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  200 TMAX = 0.9 * TOUTER(ICOUNT)
      TMIN = 1.1 * TOUTER(ICOUNT)
C THE BOUNDS ABOVE ARE CRITICAL IN ENSURING CONVERGENCE
C THEY MUST BE NEITHER TOO LARGE NOR TOO SMALL
  210 CONTINUE
      NRVRS = 1
C
  220 IF ( (C5 .GT. 0.000001) .OR. (C5 .LT. -0.000001) ) GO TO 260
C IF NOT, FIRST SOLUTION MAY BE SCALED IN THE ABSENCE OF ANY THERMAL
C    1  MISMATCH BETWEEN ADHERENDS
C IF SO, SOLUTION MUST BE REFINED BY ITERATION, SINCE THERMAL STRESS
C    1  TERMS DO NOT SCALE LINEARLY, EVEN FOR ELASTIC ADHESIVE AND
C    2  ADHERENDS
C
C APPLY SCALE FACTOR TO SOLUTION FOR ONLY ADHEREND STIFFNESS IMBALANCE
C ASCERTAIN WHETHER INTERNAL LOADS ARE CRITICAL FOR ELASTIC ADHESIVE OR
C    1  WHETHER OTHER END OF JOINT IS MORE CRITICAL FOR ADHESIVE
C PROGRAM ASSUMES ADHEREND ALLOWABLES HAVE SAME MAGNITUDE IN TENSION AS
C    1  IN COMPRESSION. DISTINCTION IS USUALLY UNIMPORTANT SINCE, IN
C    2  PRACTICAL JOINTS, RESIDUAL THERMAL STRESSES ARE UNLIKLELY TO
C    3  BREAK ADHEREND(S) RATHER THAN ADHESIVE
      RSCALE = TOUTER(1) / STROTR(1)
      IF (RSCALE .LT. 0.) RSCALE = -1. * RSCALE
      RTAUMX = TAU(1) / TAUMAX
      IF (RTAUMX .LT. 0.) RTAUMX = -1. * RTAUMX
      DO 240 N = 2, MSTEPS
      RINR = TINNER(N) / STRINR(N-1)
C NEED STRENGTH ON THIN SIDE OF STEP. HENCE THE (N-1) IN COMPARISON
      IF (RINR .LT. 0.) RINR = -1. * RINR
      IF (RINR .GT. RSCALE) RSCALE = RINR
      IF (N .EQ. MSTEPS) GO TO 230
      ROTR = TOUTER(N) / STROTR(N)
      IF (ROTR .LT. 0.) ROTR = -1. * ROTR
      IF (ROTR .GT. RSCALE) RSCALE = ROTR
  230 RTAU = TAU(N) / TAUMAX
      IF (RTAU .LT. 0.) RTAU = -1. * RTAU
      IF (RTAU .GT. RTAUMX) RTAUMX = RTAU
  240 CONTINUE
      RFCTR = RSCALE
C RFCTR IS PROPORTIONALITY CONSTANT GOVERNING ELASTIC SOLUTION
C IF RTAUMAX .GT. RSCALE, ADHESIVE PLASTICITY CAN INCREASE STRENGTH
C USUALLY ADHESIVE IS CRITICAL AT ONE END OF JOINT OR OTHER, SO RTAUMX
C    1  .GT. 1. MAY WELL JUST SIGNIFY THAT FAR END OF JOINT IS CRITICAL
C NOTE THAT PROGRAM ASSUMES THAT ANY INTERNAL ADHEREND STRESSES OF
C    1  REVERSED SIGN WITH RESPECT TO STRESS OUTSIDE THE JOINT ARE NOT
C    2  CRITICAL. IF THEY ARE, IT MEANS THAT THE JOINT WILL FAIL DUE
C    3  TO RESIDUAL THERMAL STRESSES ALONE WITHOUT ANY MECHANICAL LOADS
      IF (RSCALE .LT. RTAUMX) RFCTR = RTAUMX
      DO 250 N = 1, MSTEPS
      TOUTER(N) = TOUTER(N) / RFCTR
      TINNER(N) = TINNER(N) / RFCTR
      TAU(N) = TAU(N) / RFCTR
      GAMMA(N) = GAMMA(N) / RFCTR
      DELTAO(N) = DELTAO(N) / RFCTR
  250 DELTAI(N) = DELTAI(N) / RFCTR
      GO TO 330
C
C USE ITERATIVE SOLUTION WHEN ADHEREND THERMAL MISMATCH IS PRESENT
C ASCERTAIN WHETHER INTERNAL LOADS ARE CRITICAL FOR ELASTIC ADHESIVE OR
C    1  WHETHER OTHER END OF JOINT IS MORE CRITICAL FOR ADHESIVE.
  260 RSCALE = TOUTER(1) / STROTR(1)
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      IF (RSCALE .LT. 0.) RSCALE = -1. * RSCALE
      RTAUMX = TAU(1) / TAUMAX
      IF (RTAUMX .LT. 0.) RTAUMX = -1. * RTAUMX
      DO 280 N = 2, MSTEPS
      RINR = TINNER(N) / STRINR(N)
      IF (RINR .GT. RSCALE) RSCALE = RINR
      IF (N .EQ. MSTEPS) GO TO 270
      ROTR = TOUTER(N) / STROTR(N)
      IF (ROTR .GT. RSCALE) RSCALE = ROTR
  270 RTAU = TAU(N) / TAUMAX
      IF (RTAU .LT. 0.) RTAU = -1. * RTAU
      IF (RTAU .GT. RTAUMX) RTAUMX = RTAU
  280 CONTINUE
C CHECK ON CONVERGENCE
      R = RTAUMX
      IF (RTAUMX .LT. RSCALE) R = RSCALE
      IF ( (1.00001 .GT. R) .AND. (0.99999 .LT. R) ) GO TO 330
      V = 2. * TAUMAX
      R = (V + TAUUPR) / (V + TAULWR)
      IF ( (1.00001 .GT. R) .AND. (0.99999 .LT. R) ) GO TO 330
C IF EITHER RTAUMX OR RSCALE .GT. UNITY, TAU(1) MUST BE DECREASED
      IF ( (RTAUMX .GT. 1.00001) .OR. (RSCALE .GT. 1.00001) ) GO TO 290
C IF BOTH RTAUMX AND RSCALE ARE .LT. UNITY, TAU(1) MUST BE INCREASED
      IF ( (RTAUMX .LT. 0.99999) .AND. (RSCALE .LT. 0.99999) ) GO TO 300
C IF NEITHER CHECK IS MET, SOLUTION HAS CONVERGED
      GO TO 330
  290 TAUUPR = TAU(1)
      GO TO 310
  300 TAULWR = TAU(1)
  310 CONTINUE
C IF PROGRAM GOES BEYOND PRECEEDING CONTINUE STATEMENT, SOLUTION HAS NOT
C    1  CONVERGED
      WRITE (IOOO,320)
  320 FORMAT (1H1, 18HDIVERGENT SOLUTION)
C
C PRINT OUT RESULTS OF ELASTIC COMPUTATIONS
  330 WRITE (IOOO,340) TOUTER(1), TAUMAX, SGNLD, DELTMP
  340 FORMAT (1H1/, 5(1H0/),
     1  39H ELASTIC JOINT STRENGTH, PLOAD (LBS) = , F10.1/,
     2  49H ALLOWABLE ADHESIVE SHEAR STRESS, TAUMAX (PSI) = , F8.1/,
     3  1H , 4HN = , F4.1, 50H   N = +1 FOR TENSILE SHEAR AND -1 FOR COM
     4PRESSIVE/, 36H TEMPERATURE DIFFERENTIAL (DEG F) = , F6.1//,
     51H ,2X,1HN,1X,5HSTEPL,3X,3HTAU,4X,5HGAMMA,1X,6HDELTAO,1X,6HDELTAI,
     62X,6HTOUTER,2X,6HSTROTR,2X,6HTINNER,2X,6HSTRINR//)
      DO 360 N = 1, MSTEPS
      WRITE (IOOO,350) N, STEPL(N),TAU(N),GAMMA(N),
     1   DELTAO(N), DELTAI(N), TOUTER(N), STROTR(N), TINNER(N), STRINR(N
     2)
  350 FORMAT(1H ,I3,1X,F5.3,1X,F7.1,1X,F6.3,1X,F6.4,1X,F6.4,1X,F7.0,1X,
     1F7.0,1X,F7.0,1X,F7.0)
  360 CONTINUE
C
C RECOMPUTE SOLUTION FROM OTHER END OF JOINT, IF APPROPRIATE
C NOTE THAT, IF COMPUTER PRINTS OUT TWO SOLUTIONS TO A GIVEN PROBLEM BY
C    1  REVERSING ENDS AND RE-ANALYZING, IT IS BECAUSE THE FIRST FAILED
C    2  TO CONVERGE, EVEN IF THE ANSWERS PRINTED SEEM TO SUGGEST
C    3  OTHERWISE.  THE SECOND SOLUTION IS TO BE PREFERRED, PARTICULARLY
C    4  IF IT STARTS AT THAT END OF THE JOINT AT WHICH THE ADHESIVE
C    5  SHEAR STRESS IS AT ITS HIGHEST.
C IDENTIFY CRITICAL END OF JOINT
C AVOID REVERSING ENDS BACK AGAIN
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      IF (JFLAG .EQ. 2) GO TO 400
      IF (NRVRS .EQ. 1) GO TO 370
C IF SO, SOLUTION HAS FAILED TO CONVERGE, SO TRY AGAIN FROM OTHER END
C ACCURACY AT FAR END OF JOINT MAY BE POOR IF FAR END IS CRITICAL
      IF ((TAU(MSTEPS) .LE. TAU(1)) .AND. (TAU(MSTEPS) .GE.
     1 (-1. * TAU(1)))) GO TO 400
C IF, AT FAR END OF JOINT, TAU(MSTEPS) .GT. TAU(1) AT NEAR END,
C    1  FAILURE TO CONVERGE MAY BE SIMPLY THE RESULT OF THE FAR END
C    2  OF THE JOINT BEING MORE CRITICAL THAN THE STARTING (NEAR) END
C  REVERSE DATA AND REANALYZE
  370 DO 380 N = 1, MSTEPS
      STEP(N) = STEPL(N)
      THCKNO(N) = THICKO(N)
      THCKNI(N) = THICKI(N)
      ETOUTR(N) = ETOTR(N)
      ETINNR(N) = ETINR(N)
      STRGTR(N) = STROTR(N)
  380 STRGNR(N) = STRINR(N)
      DO 390 N = 1, NSTEPS
      STEPL(N) = STEP(MSTEPS - N)
      THICKO(N) = THCKNI(MSTEPS - N)
      THICKI(N) = THCKNO(MSTEPS - N)
      ETOTR(N) = ETINNR(MSTEPS - N)
      ETINR(N) = ETOUTR(MSTEPS - N)
      STROTR(N) = STRGNR(MSTEPS - N)
  390 STRINR(N) = STRGTR(MSTEPS - N)
      STEPL(MSTEPS) = STEP(MSTEPS)
      THICKO(MSTEPS) = 0.
      THICKI(MSTEPS) = THCKNO(1)
      ETOTR(MSTEPS) = 0.
      ETINR(MSTEPS) = ETOUTR(1)
      STROTR(MSTEPS) = 0.
      STRINR(MSTEPS) = STRGTR(1)
      V = ALPHAO
      ALPHAO = ALPHAI
      ALPHAI = V
      JFLAG = 2
      NRVRS = 0
      GO TO 60
C
C BYPASS ELASTIC-PLASTIC COMPUTATIONS IF ADHERENDS ARE MORE CRITICAL
C    1  THAN ADHESIVE
  400 IF (RSCALE .GE. RTAUMX) GO TO 820
C RECORD ELASTIC JOINT STRENGTH
      ELSTR = TOUTER(1)
C
C START ELASTIC-PLASTIC SOLUTION
C ELASTIC SOLUTION HAS IDENTIFIED CRITICAL END OF JOINT, AND REVERSED
C    1  ORDER OF DATA IF NECESSARY, SO THERE IS NO NEED FOR SUCH
C    2  CAPABILITY IN THE ELASTIC-PLASTIC SOLUTION
C ADD EXTRA LOCATIONS INSIDE STEPS TO ACCOUNT FOR POTENTIAL PLASTIC-TO-
C    1  ELASTIC AND ELASTIC-TO-PLASTIC TRANSITIONS IN ADHESIVE
  410 DO 420 N = 1, NSTEPS
      L = 3 * N
      THCKNO(L-2) = THICKO(N)
      THCKNO(L-1) = THICKO(N)
      THCKNO(L) = THICKO(N)
      THCKNI(L-2) = THICKI(N)
      THCKNI(L-1) = THICKI(N)
      THCKNI(L) = THICKI(N)
      ETOUTR(L-2) = ETOTR(N)
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      ETOUTR(L-1) = ETOTR(N)
      ETOUTR(L) = ETOTR(N)
      ETINNR(L-2) = ETINR(N)
      ETINNR(L-1) = ETINR(N)
      ETINNR(L) = ETINR(N)
      STRGTR(L-2) = STROTR(N)
      STRGTR(L-1) = STROTR(N)
      STRGTR(L) = STROTR(N)
      STRGNR(L-2) = STRINR(N)
      STRGNR(L-1) = STRINR(N)
  420 STRGNR(L) = STRINR(N)
      THCKNO(MCHECK) = 0.
      THCKNI(MCHECK) = THICKI(MSTEPS)
      ETOUTR(MCHECK) = 0.
      ETINNR(MCHECK) = ETINR(MSTEPS)
      STRGTR(MCHECK) = 0.
      STRGNR(MCHECK) = STRINR(MSTEPS)
C USE OUTER LOOP TO ADJUST MAXIMUM ADHESIVE SHEAR STRAIN LEVEL
      GAMUPR = GAMMAX
      GAMLWR = GAMMAE
C GAMUPR AND GAMLWR SERVE AS BOUNDS ON SHEAR STRAIN ACTUALLY DEVELOPED
C SET UPPER AND LOWER BOUNDS ON STRENGTH
      TUPPER = TAUMAX * OLAP * 2.
C NOTE THAT THE FACTOR 2. ACCOUNTS FOR BONDING ON BOTH SIDES OF
C     1  ADHERENDS.  IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
      TLOWER = ELSTR
C TMAX .EQ. FULLY-PLASTIC JOINT STRENGTH
C TMIN .EQ. PERFECTLY-ELASTIC JOINT STRENGTH
      ICHECK = 0
      JCHECK = 10
C NEED TO SET DIFFERENT VALUES FOR ICHECK AND JCHECK WITH NEITHER
C     1  EQUAL TO EITHER 1 OR 2
      DO 760 I = 1, 50
      IF ( (KADHSV .EQ. 1) .AND. (I .GT. 1) ) GO TO 770
C THIS INSTRUCTION PRINTS OUT SOLUTION FOR POTENTIAL BOND SHEAR STRENGTH
      TMAX = TUPPER
      TMIN = TLOWER
      GAMMA(1) = (GAMUPR + GAMLWR) / 2.
      IF ( (KADHSV .EQ. 1) .OR. (I .EQ. 1) ) GO TO 440
      IF (ICHECK .NE. JCHECK) GO TO 450
      IF (ICHECK .EQ. 1) GO TO 430
C IF NOT, ICHECK .EQ. 2 AND LOAD HAS BEEN TOO HIGH FOR TWO CONSECUTIVE
C     1  ITERATIONS
      GAMMA(1) = (GAMMA(1) + GAMLWR) / 2.
      ICHECK = 2
      GO TO 450
C IF ICHECK .EQ. 1, LOAD HAS BEEN TOO LOW FOR TWO CONSECUTIVE ITERATIONS
  430 GAMMA(1) = (GAMMA (1) + GAMUPR) / 2.
      ICHECK = 1
      GO TO 450
  440 GAMMA(1) = GAMMAX
C SET INITIAL CONDITIONS
  450 TOUTER(1) = (TUPPER + TLOWER) / 2.
      TINNER(1) = 0.
      TAU(1) = TAUMAX
      DELTAO(1) = 0.
      DELTAI(1) = SGNLD * GAMMA(1) * ETA
      DO 700 IFLAG = 1, NSTEPS
      J1 = 3 * IFLAG - 2
      J2 = J1 + 3
      SCHECK = 1000000000000000.
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      DO 660 NCOUNT = 1, 50
C USUALLY 20 CYCLES OF ITERATION WERE SUFFICIENT AT THIS POINT
C MIDDLE LOOP ADJUSTS LOAD LEVEL
C CHECK ON CONVERGENCE OF TOUTER(J1)
      R = TOUTER(J1) / SCHECK
      IF ( (1.000000001 .GT. R) .AND. (0.999999999 .LT. R) ) GO TO 670
      V11 = TOUTER(1)
      V10 = -1. * V11
      DO 600 N = IFLAG, NSTEPS
C INNERMOST LOOP COMPUTES JOINT STRENGTH
      L = 3 * N - 2
      STEP(L) = STEPL(N)
      STEP(L+1) = 0.
      STEP(L+2) = 0.
C IF ADHESIVE IS NOT LOADED INTO PLASTIC ZONE IN LATER STEPS OF JOINT,
C    1  BYPASS SUCH COMPUTATIONS AND PROCEED TO PERFECTLY-ELASTIC SOLUTI
      V8 = GAMMA(L)
      IF ( (V8 .LE. GAMMAE) .AND. (V8 .GE. C7) ) GO TO 510
      XP = 1000000000.
      MFLAG = 0
C SOLVE FOR MAXIMUM POSSIBLE EXTENT OF PLASTIC ADHESIVE ZONE
C    1  AND COMPARE WITH STEP LENGTH
      V4 = ETOTR(N)
      V5 = ETINR(N)
      V6 = TOUTER(L)
      V7 = TINNER(L)
      V9 = STEP(L)
      V = (1. / V4 + 1. / V5) / ETA
      A = TAUMAX * V
C IF BONDED ON ONE SIDE OF JOINT ONLY, DIVIDE A BY 2.
      B = (C5 * SGNLD - V6 / V4 + V7 / V5) / ETA
C NOTE THAT B SHOULD BE NEGATIVE AT AND NEAR MORE CRITICAL END OF JOINT
C IF NOT, SOLUTION IS PROCEEDING FROM WRONG END OF JOINT
C HENCE NEED FOR PRIOR ELASTIC SOLUTION TO IDENTIFY CRITICAL END
      IF (V8 .LT. 0.) GO TO 460
C PROCEDURE FOR POSITIVE PLASTIC ADHESIVE SHEAR STRAINS
      IF (B .GE. 0.) GO TO 470
      C = V8 - GAMMAE
      D = B**2 - 4. * A * C
      IF (D .LT. 0.) GO TO 470
C IF SO, PLASTIC ZONE IS UNBOUNDED, AS AT FAR END OF JOINT
      XP = (-1. * B - DSQRT(D)) / (2. * A)
      GO TO 470
C PROCEDURE FOR NEGATIVE PLASTIC ADHESIVE SHEAR STRAINS
  460 IF (B .LE. 0.) GO TO 470
      C = V8 + GAMMAE
      D = B**2 + 4. * A * C
      IF (D .LT. 0.) GO TO 470
C IF SO, PLASTIC ZONE IS UNBOUNDED, AS AT FAR END OF JOINT
      XP = (B - DSQRT(D)) / (2. * A)
  470 IF (XP .GE. V9) GO TO 480
C IF SO, ADHESIVE IS FULLY-PLASTIC THROUGHOUT THAT STEP
C IF NOT, BREAK UP STEP INTO PLASTIC AND ELASTIC PORTIONS
      MFLAG = 1
      STEP(L) = XP
      STEP(L+1) = V9 - XP
      V9 = XP
C MAY HAVE TO DECREASE STEP(3*N-1) AND ADD TO STEP(3*N) LATER
C
C PROCEDURE FOR FULLY-PLASTIC STEP OR STEP PORTION
C THIS SERIES OF EQUATIONS HOLDS REGARDLESS OF SIGN OF SHEAR STRESS
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C     1  GRADIENT AT START OF STEP
  480 DELT = 2. * TAU(L)  * V9
C THE USE OF TAU(L) INSTEAD OF TAUMAX COVERS REVERSAL OF SIGN
C FACTOR 2. ACCOUNTS FOR BONDING ON BOTH SIDES OF *INNER* ADHEREND.
C     1  IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
        L = L + 1
        TOUTER(L) = V6 - DELT
        TINNER(L) = V7 + DELT
        GAMMA(L) = GAMMA(L-1) + B * V9 + TAU(L-1) * V * (V9**2)
        TAU(L) = TAU(L-1)
        DELTAO(L) = DELTAO(L-1) + C3 * V9 + SGNLD * (V6 * V9 - TAU(L) *
     1  (V9**2) / 2.) / V4
        DELTAI(L) = DELTAI(L-1) + C4 * V9 + SGNLD * (V7 * V9 + TAU(L) *
     1  (V9**2) / 2.) / V5
C NOTE THAT USE OF TAU(L) INSTEAD OF TAUMAX AUTOMATICALLY ACCOUNTS FOR
C     1  SIGN OF ADHESIVE SHEAR STRESS
        IF (MFLAG .EQ. 1) GO TO 490
C IF NOT, STEP IS PLASTIC THROUGHOUT
        L1 = L + 1
        L2 = L + 2
        TOUTER(L1) = TOUTER(L)
        TOUTER(L2) = TOUTER(L)
        TINNER(L1) = TINNER(L)
        TINNER(L2) = TINNER(L)
        TAU(L1) = TAU(L)
        TAU(L2) = TAU(L)
        GAMMA(L1) = GAMMA(L)
        GAMMA(L2) = GAMMA(L)
        DELTAO(L1) = DELTAO(L)
        DELTAO(L2) = DELTAO(L)
        DELTAI(L1) = DELTAI(L)
        DELTAI(L2) = DELTAI(L)
  490   IF (N .EQ. NSTEPS) GO TO 500
        IF (TOUTER(L) .LT. V10) GO TO 620
        IF (TINNER(L) .LT. V10) GO TO 610
C NOTE THAT THESE CONVERGENCE CHECKS ARE CRITICAL
  500 IF (MFLAG .EQ. 1) GO TO 510
        GO TO 590
C
C PROCEDURE FOR PERFECTLY-ELASTIC ZONE
C IDENTIFY WHETHER STEP IS ELASTIC-PLASTIC OR FULLY ELASTIC THROUGHOUT
  510 K = L - 3 * N + 2
C K .EQ. 0 CORRESPONDS TO NO PLASTIC ZONE AT NEAR END OF JOINT
C SET INITIAL CONDITIONS AT START OF STEP
        V4 = ETOTR(N)
        V5 = ETINR(N)
        V6 = TOUTER(L)
        V7 = TINNER(L)
        ALAMDA = DSQRT(C2 * (1. / V4 + 1. / V5))
        LFLAG = 0
C COMPUTE VALUES AT FAR END OF ELASTIC ZONE
        A = TAU(L)
        B = (V7 / V5 - V6 / V4 + C5 * SGNLD) * C1 / ALAMDA
C NOTE THAT SGNLD SIGNIFIES WHETHER SHEAR LOAD IS TENSILE OR COMPRESSIVE
        C = STEP(L)
        D = ALAMDA * C
        E = DSINH(D)
        F = DCOSH(D)
        TAU(L+1) = A * F + B * E
        IF ( (TAU(L+1) .LE. TAUMAX) .AND. (TAU(L+1)  .GE. C10) )
     1  GO TO 540
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C IF NOT, ELASTIC STEP SIZE IS EXCESSIVE.  REDUCE BY ITERATION
      ELMAX = C
      ELMIN = 0.
      DO 520 LCOUNT = 1, 100
      EL = (ELMAX + ELMIN) / 2.
      D = ALAMDA * EL
      E = DSINH(D)
      F = DCOSH(D)
      TCHECK = A * F + B * E
      IF ( (TCHECK .GT. TAUMAX) .OR. (TCHECK .LT. C10) ) ELMAX = EL
      IF ( (TCHECK .LT. TAUMAX) .AND.  (TCHECK .GT. C10) ) ELMIN = EL
      R = ELMIN / ELMAX
      IF ( (1.000000001 .GT. R) .AND. (0.999999999 .LT. R) ) GO TO 530
  520 CONTINUE
  530 STEP(L) = EL
      STEP(L+1) = STEP(L+1) + C - EL
      LFLAG = 1
      IF (TCHECK .GT. 0.) TAU(L+1) = TAUMAX
      IF (TCHECK .LT. 0.) TAU(L+1) = C10
  540 DELT = (2. / ALAMDA) * (A * E + B * (F - 1.))
C FACTOR 2. ACCOUNTS FOR BONDING ON BOTH SIDES OF "INNER" ADHEREND.
C     1  IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
      L = L + 1
      TOUTER(L) = V6 - DELT
      TINNER(L) = V7 + DELT
      DELDLT = (2. / (ALAMDA**2)) * (A * (F - 1.) + B * (E - D))
C FACTOR OF 2. ACCOUNTS FOR BONDING ON BOTH SIDES OF INNER ADHEREND.
C     1  IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
      DELTAO(L) = DELTAO(L-1) + C3 * EL + SGNLD * (V6 * EL - DELDLT) /V4
      DELTAI(L) = DELTAI(L-1) + C4 * EL + SGNLD * (V7 * EL + DELDLT) /V5
      GAMMA(L) = TAU(L) / G
      IF (LFLAG .EQ. 1) GO TO 550
C IF NOT, THERE IS NO (SECOND) PLASTIC ZONE AT FAR END OF STEP
      L1 = L + 1
      TOUTER(L1) = TOUTER(L)
      TINNER(L1) = TINNER(L)
      TAU(L1) = TAU(L)
      GAMMA(L1) = GAMMA(L)
      DELTAO(L1) = DELTAO(L)
      DELTAI(L1) = DELTAI(L)
      IF (K .EQ. 1) GO TO 550
C IF NOT, THERE WAS NO (FIRST) PLASTIC ZONE AT NEAR END OF JOINT
      L2 = L + 2
      TOUTER(L2) = TOUTER(L)
      TINNER(L2) = TINNER(L)
      TAU(L2) = TAU(L)
      GAMMA(L2) = GAMMA(L)
      DELTAO(L2) = DELTAO(L)
      DELTAI(L2) = DELTAI(L)
  550 IF (N .EQ. NSTEPS) GO TO 560
      IF  (TOUTER(L) .LT. V10) GO TO 620
      IF (TINNER(L) .LT. V10) GO TO 610
C NOTE THAT THESE CONVERGENCE CHECKS ARE CRITICAL
C IF V10 IS EITHER TOO LARGE OR TOO SMALL, CONVERGENCE FAILS
  560 IF (LFLAG .EQ. 1) GO TO 570
      GO TO 590
C
C PROCEDURE FOR (SECOND) PLASTIC ZONE AT FAR END OF STEP
  570 V9 = STEP(L)
      DELT = 2. * TAU(L) * V9
C  FACTOR 2. ACCOUNTS FOR BONDING ON BOTH SIDES OF "INNER" ADHEREND.
```

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```
C     1  IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
C SET INITIAL CONDITIONS AT START OF STEP
         V4 = ETOTR(N)
         V5 = ETINR(N)
         V6 = TOUTER(L)
         V7 = TINNER(L)
         L = L + 1
         TOUTER(L) = V6 - DELT
         TINNER(L) = V7 + DELT
         A = (TAU(L-1) / ETA) * (1./V4 + 1./V5)
C NOTE THE USE OF TAU(L-1) INSTEAD OF TAUMAX IN ORDER TO ACCOUNT
C     1  AUTOMATICALLY FOR THE SIGN OF THE SHEAR STRESS
C IF BONDED ON ONE SIDE OF JOINT ONLY, DIVIDE A BY 2.
         B = (C5 * SGNLD - V6 / V4 + V7 / V5) / ETA
         GAMMA(L) = GAMMA(L-1) + B * V9 + A * (V9**2)
         TAU(L) = TAU(L-1)
         DELTAO(L) = DELTAO(L-1) + C3 * V9 + SGNLD * (V6 * V9 - TAU(L) *
        1  (V9**2) / 2.) / V4
         DELTAI(L) = DELTAI(L-1) + C4 * V9 + SGNLD * (V7 * V9 + TAU(L) *
        1  (V9**2) / 2.) / V5
C IF THERE HAS BEEN NO PLASTIC ZONE AT START OF STEP, TRANSFER VALUES
C     1  JUST COMPUTED ACROSS TO LAST SUBDIVISION IN STEP
C THIS IS NECESSARY TO PROVIDE INPUT DATA FOR START OF NEXT STEP
         IF (K .EQ. 1) GO TO 580
         L1 = L + 1
         TOUTER(L1) = TOUTER(L)
         TINNER(L1) = TINNER(L)
         TAU(L1) = TAU(L)
         GAMMA(L1) = GAMMA(L)
         DELTAO(L1) = DELTAO(L)
         DELTAI(L1) = DELTAI(L)
    580  IF (N .EQ. NSTEPS) GO TO 630
         IF (TOUTER(L) .LT. V10) GO TO 620
         IF (TINNER(L) .LT. V10) GO TO 610
C NOTE THAT THESE CONVERGENCE CHECKS ARE CRITICAL
    590  IF (N .EQ. NSTEPS) GO TO 630
    600  CONTINUE
C PROCEDURE FOR WHEN LOAD ESTIMATE IS TOO HIGH
    610  TMAX = TOUTER(J1)
         SCHECK = TOUTER(J1)
         TOUTER(J1) = (TMAX + TMIN) / 2.
         GO TO 660
C PROCEDURE FOR WHEN LOAD ESTIMATE IS TOO LOW
    620  TMIN = TOUTER(J1)
         SCHECK = TOUTER(J1)
         TOUTER(J1) = (TMAX + TMIN) / 2.
         GO TO 660
C
C CHECK WHETHER OR NOT PRECISELY 100 PERCENT OF LOAD HAS TRANSFERRED
    630  R1 = TOUTER(1) / TINNER(MCHECK)
         R2 = TCHECK / TINNER(MCHECK)
         IF ( (1.000001 .GT. R1) .AND. (0.999999 .LT. R1) .AND.
        1  (1.000001 .GT. R2) .AND. (0.999999 .LT. R2) ) GO TO 710
         IF (TOUTER(1) .LT. TINNER(MCHECK)) GO TO 640
C NOTE THAT, HERE, LOAD IS TAKEN TO BE POSITIVE WHETHER TENSILE OR NOT
C     1  FOR A NEGATIVE LOAD, PRECEDING INSTRUCTION SHOULD BE
C     2  INTERCHANGED WITH THE FOLLOWING ONE
C IF SO, LOAD ESTIMATE IS TOO LOW
C IF REVERSE HOLDS, LOAD ESTIMATE IS TOO HIGH
         GO TO 590
C PROCEDURE FOR WHEN LOAD ESTIMATE IS TOO LOW
```

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```
  640 TMIN = TOUTER(J1)
      TOUTER(J1) = (TMAX + TMIN) / 2.
      TCHECK = TINNER(MCHECK)
      GO TO 660
C PROCEDURE FOR WHEN LOAD ESTIMATE IS TOO HIGH
  650 TMAX = TOUTER(J1)
      TOUTER(J1) = (TMAX + TMIN) / 2.
      TCHECK = TINNER(MCHECK)
  660 CONTINUE
C CONVERGENCE WILL NOT PROCEED TO FAR END OF JOINT IN SINGLE PASS
C    1  BECAUSE OF NUMERICAL ACCURACY PROBLEMS.  REMEDY IS TO FREEZE
C    2  EARLIER VALUES, WHICH HAVE CONVERGED, AND TO PERTURB SLIGHTLY
C    3  INTERMEDIATE VALUES, AND TO CHECK FOR CONVERGENCE AT THE FAR END
      TMAX = TUPPER
      TMIN = -1. * TMAX
      GO TO 700
  670 IF (TOUTER(J2) .GT. 0.) GO TO 680
      IF (TOUTER(J2) .LT. 0.) GO TO 690
      TMAX = TOUTER(1) / 10.
      TMIN = -1. * TMAX
      GO TO 700
  680 TMAX = 1.1 * TOUTER(J2)
      TMIN = 0.9 * TOUTER(J2)
      GO TO 700
  690 TMAX = 0.9 * TOUTER(J2)
      TMIN = 1.1 * TOUTER(J2)
C THE BOUNDS ABOVE ARE CRITICAL IN ENSURING CONVERGENCE
C THEY MUST BE NEITHER TOO LARGE NOR TOO SMALL
  700 CONTINUE
C
C ASCERTAIN WHETHER INTERNAL LOADS ARE CRITICAL FOR ELASTIC-PLASTIC
C    1  ADHESIVE
  710 RSCALE = TOUTER(1) / STRGTR(1)
      IF (RSCALE .LT. 0.) RSCALE = -1. * RSCALE
      RGAMAX = GAMMA(1) / GAMMAX
      IF (RGAMAX .LT. 0.) RGAMAX = -1. * RGAMAX
      DO 730 N = 2, MCHECK
      RINR = TINNER(N) / STRGNR(N-1)
C AT EACH STEP TRANSITION NEED THE THINNER SECTION.  HENCE THE (N-1)
      IF (RINR .LT. 0.) RINR = -1. * RINR
      IF (RINR .GT. RSCALE) RSCALE = RINR
      IF (N .EQ. MCHECK) GO TO 720
      ROTR = TOUTER(N) / STRGTR(N)
      IF (ROTR .LT. 0.) ROTR = -1. * ROTR
      IF (ROTR .GT. RSCALE) RSCALE = ROTR
  720 RGAMX = GAMMA(N) / GAMMAX
      IF (RGAMX .LT. 0.) RGAMX = -1. * RGAMX
      IF (RGAMX .GT. RGAMAX) RGAMAX = RGAMX
  730 CONTINUE
C
C IF UPPER AND LOWER BOUNDS ON JOINT LOAD HAVE COALESCED,
C    1  NO MORE CONVERGENCE IS POSSIBLE.  PRINT OUT RESULTS.
      R = TUPPER / TLOWER
      IF ( (1.000000001 .GT. R) .AND. (0.999999999 .LT. R) ) GO TO 770
C ADJUST MAXIMUM ADHESIVE SHEAR STRAIN IF ADHEREND STRENGTH GOVERNS OVER
C    1  ADHESIVE STRENGTH CONSIDERATIONS
      IF ( (RSCALE .GT. 1.0001) .OR. (RGAMAX .GT. 1.0001) )
     1  GO TO 740
      IF ( (RSCALE .LT. 0.9999) .AND. (RGAMAX .LT. 0.9999) )
     1  GO TO 750
C IF NEITHER OF THESE CHECKS IS MET, SOLUTION HAS CONVERGED.  PRINT OUT.
```

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```
      GO TO 770
C IF NOT, REITERATE
  740 GAMUPR = GAMMA(1)
      TUPPER = TOUTER(1)
      JCHECK = 2
      GO TO 760
  750 GAMLWR = GAMMA(1)
      TLOWER = TOUTER(1)
      JCHECK = 1
  760 CONTINUE
C IF PROGRAM GOES PAST THIS CONTINUE STATEMENT, CONVERGENCE HAS FAILED
      WRITE (IOOO,320)
C
C PRINT OUT RESULTS OF ELASTIC-PLASTIC COMPUTAIONS
  770 WRITE (IOOO,780) TOUTER(1), GAMMAX, SGNLD, DELTMP
  780 FORMAT (1H1/, 5(1H0/),
     1  47H ELASTIC-PLASTIC JOINT STRENGTH, PLOAD (LBS) = , F10.1/,
     2  43H ALLOWABLE ADHESIVE SHEAR STRAIN, GAMMAX = , F5.2/,
     3  1H , 4HN = , F4.1, 50H   N = +1 FOR TENSILE SHEAR AND -1 FOR COM
     4PRESSIVE/, 36H TEMPERATURE DIFFERENTIAL (DEG F) = , F6.1//,
     5  1H ,2H N,1X,5HSTEPL,3X,3HTAU,4X,5HGAMMA,1X,6HDELTAO,1X,6HDELTAI,
     62X,6HTOUTER,2X,6HSTROTR,2X,6HTINNER,2X,6HSTRINR//)
      DO 800 N = 1, MCHECK
      WRITE (IOOO,790) N, STEP(N),TAU(N),GAMMA(N),
     1    DELTAO(N), DELTAI(N), TOUTER(N), STRGTR(N), TINNER(N), STRGNR(N
     2)
  790 FORMAT (I3,1X,F5.3,1X,F7.1,1X,F6.3,1X,F6.4,1X,F6.4,1X,F7.0,1X,
     1F7.0,1X,F7.0,1X,F7.0)
  800 CONTINUE
      IF (KADHSV .EQ. 1) GO TO 820
      IF (RSCALE .LT. RGAMAX) GO TO 820
C IF NOT, COMPUTE POTENTIAL BOND STRENGTH OF ADHESIVE
      KADHSV = 1
      DO 810 K = 1, MSTEPS
      STROTR(K) = 10000000000000000000000.
  810 STRINR(K) = 10000000000000000000000.
      GO TO 70
  820 CONTINUE
      STOP
      END
```

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APPENDIX B

DERIVATION OF WEAROUT MODEL

<u>Derivation of the Wearout Model</u>

Two assumptions are made. First assume that the damage rate accumulation may be approximate by a power-law growth equation (B-1)

$$\frac{\partial C}{\partial t} = A_o F^{2r} C^r \qquad \text{(B-1)}$$

where C is the dimension of the critical damage zone and F is the critical load.

Second, assume that the critical load is related to an apparent toughness parameter, K, by

$$F \sqrt{C} = K \qquad \text{(B-2)}$$

These assumptions appeal to intuition because of their similarity to relations often used in classical work (for instance Reference B-1). Namely,

$$\frac{F}{A} = \frac{K}{\sqrt{\pi C}} \qquad \text{(B-3)}$$

$$\frac{\partial C}{\partial t} = A_1 K^{2r} \qquad \text{(B-4)}$$

From equation (B-3)

$$K^{2r} = \frac{\pi^r}{A^{2r}} F^{2r} C^r \qquad \text{(B-5)}$$

Putting (B-5) into (B-4) gives

$$\frac{\partial C}{\partial t} = A_2 F^{2r} C^r \qquad \text{(B-6)}$$

which is the classical relation which furnishes the intuitive appeal of the first assumption. Equation (B-3) is the classical relation which provides the intuitive appeal of the second assumption.

Integrating (B-1) gives equation (B-7)

$$\int_{C_o}^{C} \frac{\partial C}{C^r} = \int_{t_o}^{t} A_o F^{2r} \partial t \qquad \text{(B-7)}$$

Since the spectrum was developed as a random process that preserved the expected cumulative statistics for the F-15, F(t) is a stationary random process and the right hand side of (B-7) becomes

$$A_3 (t - t_o) \qquad \text{(B-8)}$$

Thus (B-7) becomes

$$\frac{1}{C_o^{r-1}} + \frac{1}{C^{r-1}} = A_3 (r - 1) (t - t_o) \qquad \text{(B-9)}$$

From (B-2)

$$C^{r-1)} = \frac{K^{2(r-1)}}{F^{2(r-1)}} \qquad \text{(B-10)}$$

Putting (B-10) into (B-9) gives

$$F(t_o)^{2(r-1)} - F(t)^{2(r-1)} = A_4 (r - 1) (t - t_o) \qquad \text{(B-11)}$$

Assume the initial strength distribution is Weibull

$$P [F(t_o) > F] = \exp - [F/\beta_s]^{\alpha_s} \qquad \text{(B-12)}$$

To produce the time dependent residual strength function use (B-11) as shown below,

$$P\ [F(t) > F] = P\ \{[F(t_o)^{2(r-1)} - A_4\ (r-1)(t-t_o)]^{\frac{1}{2(r-1)}} > F\} \tag{B-13}$$

$$= P\ \{[F(t_o)^{2(r-1)} - A_4\ (r-1)(t-t_o)] > F^{2(r-1)}\}$$

$$= P\ \{F(t_o) > [F^{2(r-1)} + A_4\ (r-1)(t-t_o)]^{\frac{1}{2(r-1)}}\}$$

But the probability statement in (B-13) can be expressed by direct substitution into (B-12) as,

$$P\ [F(t) > F] = \exp - \left[\frac{F^{2(r-1)} + A_4 (r-1)(t-t_o)}{\beta_s^{\,2(r-1)}}\right]^{\alpha_f} \tag{B-14}$$

where

$$\alpha_f = \frac{\alpha_s}{2(r-1)}$$

Another relation is needed to allow the determination of A_4. This relation is provided by showing that (B-14) is approximately equal to a Weibull distribution for fatigue lifetime if fatigue failures are obtained at a load level $F_{TRU} \le \beta_s/2$, which is the case for joints used in this program. First take $t_o = 0$ and rewrite (B-14) as,

$$P\,[F(t) > F_{TRU}] = \exp - \left\{ \frac{t}{\left[\dfrac{\beta_s^{\,2(r-1)}}{A_4\,(r-1)} \right]} + \left(\frac{F_{TRU}}{\beta_s}\right)^{2(r-1)} \right\}^{\alpha_f} \tag{B-15}$$

$$= \exp - \left\{ \frac{t}{\left[\dfrac{\beta_s^{\,2(r-1)}}{A_4\,(r-1)} \right]} + \text{error} \right\}^{\alpha_f}$$

$$\simeq \exp \left\{\frac{t}{\beta_f}\right\}^{\alpha_f} = P\,(T > t)$$

where

$$\beta_f = \frac{\beta_s^{\,2(r-1)}}{A_4\,(r-1)} \tag{B-16}$$

Equation (B-16) is the needed relation.

REFERENCES

B-1 Clark, William G., Jr., "Fracture Mechanics in Fatigue," Experimental Mechanics, Sept. 1971, pp. 421-428.

APPENDIX C

COMPUTER PROGRAM ABDMATM - COMPOSITE LAMINATE PROPERTY CHARACTERIZATION

C.1 Program Description

Procedure ABDMATM calculates the initial laminate elastic moduli, stiffness matrix [A], bending extensional matrix [B], and flexural stiffness matrix [D]. The above output is valid for any laminate stacking sequence or multi-material system.

A note of caution is directed toward the application of the laminate elastic properties (E_x, E_y, G_{xy}, V_{xy}); in design it must be realized that the four elastic constancs are sufficient in number to adequately characterize only an orthotropic laminate. All laminates of higher anisotropy (which is the case if a laminate does not possess a balanced and symmetric stacking) require a number of elastic constants greater than four to adequately characterize their bending-shear-extensional behavior.

C.2 Input Instructions:

- The data required are the material characteristics of the individual unidirectional material systems involved.

  E_{11}, E_{22}, U1, and G

  where:

  E_{11} = 0° ply longitudinal (fiber) modulus
  E_{22} = 0° ply transverse (matrix) modulus
  U1 = major Poisson's ratio
  G = shear modulus

- The program is conversational in nature and generates its own input data instructions.

C.3 Program Listing

The program listing follows:

```
10$AD
20 DIMENSIØN AH(40),TH(40),QBAR(40,3,3),Q11(40),Q22(40),Q12(40)
30 DIMENSIØN AT(40),AZ(3,3),U1(40),G(40)      ,AZZ(3,3),AZZZ(3,3)
40&,A(3,3),B(3,3),D(3,3),AØT(3,3),Q66(40) ,ANT(8),E1(40),E2(40)
50&,AT3(3,3),AI(3,3),AL(3,3)
60 ØUTPUT,'HØW MANY PRØBLEMS DØ YØU WISH TØ RUN'
70 READ, KPR
80 DØ 190 IIK = 1,KPR
90 ØUTPUT,'HØW MANY PLIES IN YØUR LAMINATE?'
100 READ,MA
110 IF(IIK.GT.1) GØ TØ 1412
120 ØUTPUT,'AFTER EACH QUESTIØN MARK(?) INPUT'
130 ØUTPUT,'THICKNESS,PLY ØRIENTATIØN,AND THE'
140 ØUTPUT,'NUMBER 0 ØR 1..............'
150 ØUTPUT,'INPUT 1 FØR THE FIRST PLY AND FØR'
160 ØUTPUT,'EACH PLY WHICH HAS DIFFERENT MATL'
170 ØUTPUT,'PRØPERTIES FRØM THE PREVIØUS PLY.'
180 ØUTPUT,'AFTER INPUTTING A 1 THE MATL'
190 ØUTPUT,'PRØPERTIES ARE DESIRED'
200 ØUTPUT,'INPUT E1,E2,U1,G.....AFTER ?'
210 ØUTPUT,'FØR ALL PLIES AFTER THE 1ST'
220 ØUTPUT,'IF THE MATL PRØPERTIES ARE'
230 ØUTPUT,'THE SAME INPUT A 0(ZERØ) '
240 ØUTPUT,'THEN INPUT A NEW PLY THICKNESS,'
250 ØUTPUT,'ØRIENTATIØN AND A 0 ØR 1 AGAIN.'
260 1412 CØNTINUE
270 DØ 149 IIK=1,MA
280 READ,AT(IIK),TH(IIK),JK
290 IF(IIK.EQ.1)GØ TØ 148
300 IF(JK.EQ.1)GØ TØ 148
310 E1(IIK)=E1(IIK-1)
320 E2(IIK)=E2(IIK-1)
330 U1(IIK)=U1(IIK-1)
340 G(IIK)=G(IIK-1)
350 GØ TØ 149
360 148 READ,E1(IIK),E2(IIK),U1(IIK),G(IIK)
370 149 CØNTINUE
380 MB=MA+1
390 DØ 50 I2 = 1,MB
400 AH(I2) = 0.0
410 50 CØNTINUE
420  DØ 60 I3 =2,MB
430 AH(I3) =AT(I3-1) +AH(I3-1)
440 60 CØNTINUE
450 AHK = AH(MB)/2.0
460 DØ 70 I4 = 1,MB
470 AH(I4) =AH(I4) - AHK
```

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```
AIT = 2.0*AHK
70 CØNTINUE
DØ 80 I5 =1,MA
U2 = E2(I5)/E1(I5)*U1(I5)
DEL = 1.0 -U1(I5)*U2
Q11(I5) = E1(I5)/DEL
Q22(I5) = E2(I5)/DEL
Q12(I5) = Q11(I5)*U2
Q66(I5) = G(I5)
CØN = TH(I5) * (3.1415926536D0/180.0D0)
CØ = DCØS(CØN)
CØ2 = CØ**2
CØ3 = CØ**3
CØ4 = CØ2**2
SI = DSIN(CØN)
SI2 = SI**2
SI3 = SI**3
SI4 = SI2**2
SICØ =SI2 * CØ2
QBAR(I5,1,1) = Q11(I5)*CØ4+2.0*(Q12(I5)+2.0*Q66(I5))*SICØ+
&Q22(I5)*SI4
QBAR(I5,1,2) = (Q11(I5)+Q22(I5)-4.0*Q66(I5))*SICØ+
&Q12(I5)*(SI4+CØ4)
QBAR(I5,1,3) = (Q11(I5) - Q12(I5) - 2.0*Q66(I5))*CØ3*SI +
&(Q12(I5) - Q22(I5) + 2.0*Q66(I5))*SI3*CØ
QBAR(I5,2,1) = QBAR(I5,1,2)
QBAR(I5,2,2) = Q11(I5)*SI4+2.0*(Q12(I5)+2.0*Q66(I5))*SICØ+
&Q22(I5)*CØ4
QBAR(I5,2,3) = (Q11(I5) - Q12(I5) - 2.0*Q66(I5))*SI3*CØ +
&(Q12(I5) - Q22(I5) + 2.0*Q66(I5))*CØ3*SI
QBAR(I5,3,1) = QBAR(I5,1,3)
QBAR(I5,3,2) = QBAR(I5,2,3)
QBAR(I5,3,3) = (Q11(I5) + Q22(I5) - 2.0*Q12(I5) - 2.0*Q66(I5))*
&SICØ + Q66(I5)*(SI4+CØ4)
80 CØNTINUE
DØ 100 I6 = 1,3
DØ 90 J6 =1,3
A(I6,J6) =0.
B(I6,J6) = 0.0
D(I6,J6) = 0.
AØT(I6,J6) = 0.
90 CØNTINUE
100 CØNTINUE
DØ 130 I6 =1,3
DØ 120 J6 =1,3
DØ 110 NN =1,MA
AZ(I6,J6)=AH(NN+1)-AH(NN)
AZZ(I6,J6)=(AH(NN+1)**2-AH(NN)**2)/2.
AZZZ(I6,J6)=(AH(NN+1)**3-AH(NN)**3)/3.
A(I6,J6)=A(I6,J6)+QBAR(NN,I6,J6)*AZ(I6,J6)
B(I6,J6)=B(I6,J6)+QBAP(NN,I6,J6)*AZZ(I6,J6)
```

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```
D(I6,J6)=D(I6,J6)+QBAR(NN,I6,J6)*AZZZ(I6,J6)
110 CØNTINUE
AT3(I6,J6)=A(I6,J6)/ATT
120 CØNTINUE
130 CØNTINUE
C
C  *******CØMPUTE THE A/T INVERSE MATRIX
C
 DET=(AT3(1,1)*AT3(2,2)*AT3(3,3))+(AT3(1,2)*AT3(2,3)*AT3(3,1))
&  +(AT3(1,3)*AT3(2,1)*AT3(3,2))-(AT3(1,3)*AT3(2,2)*AT3(3,1))
& -(AT3(1,1)*AT3(2,3)*AT3(3,2))-(AT3(1,2)*AT3(2,1)*AT3(3,3))
   AL(1,1)=(AT3(2,2)*AT3(3,3)-AT3(2,3)*AT3(3,2))/DET
   AL(1,2)=(AT3(2,3)*AT3(3,1)-AT3(2,1)*AT3(3,3))/DET
   AL(1,3)=(AT3(2,1)*AT3(3,2)-AT3(2,2)*AT3(3,1))/DET
   AL(2,2)=(AT3(1,1)*AT3(3,3)-AT3(1,3)*AT3(3,1))/DET
   AL(2,3)=(AT3(1,2)*AT3(3,1)-AT3(1,1)*AT3(3,2))/DET
   AL(3,3)=(AT3(1,1)*AT3(2,2)-AT3(1,2)*AT3(2,1))/DET
   AL(2,1)=AL(1,2)
   AL(3,1)=AL(1,3)
   AL(3,2)=AL(2,3)
  DØ 270 I=1,3
  DØ 270 J=1,3
   AI(I,J)=AL(I,J)/ATT
 270 CØNTINUE
   FE1=1.0/AL(1,1)
   FU1=-FE1*AL(1,2)
   FE2=1.0/AL(2,2)
   FG=1.0/AL(3,3)
PRINT2
2 FØRMAT(////,16H      A MATRIX  ,//)
PRINT1,((A(M,N),N=1,3),M=1,3)
PRINT3
3 FØRMAT(///,16H      B MATRIX  ,//)
PRINT1,((B(M,N),N=1,3),M=1,3)
PRINT4
4 FØRMAT(///,16H      D MATRIX  ,//)
PRINT1,((D(M,N),N=1,3),M=1,3)
PRINT5
5 FØRMAT(///,18H      A/T MATRIX  ,//)
PRINT1,((AT3(M,N),N=1,3),M=1,3)
1 FØRMAT(E10.3,5X,E10.3,5X,E10.3,/)
  ØUTPUT," "
  ØUTPUT,"FØLLØWING ARE THE AVERAGE LAMINATE PRØPERTIES"
ØUTPUT," "
PRINT20,FE1,FE2,FG,FU1
20 FØRMAT('E11=  ',E10.2,5X,'E22=  ',E10.2,5X,'G=  ',E10.2,5X,
&'NU12=  ',F4.2)
ØUTPUT," "
190 CØNTINUE
  END
```

GP74-1037-173

APPENDIX D

CALCULATION OF WEIBULL PARAMETERS

D.1 Calculation of Weibull Parameters

The calculation of the Weibull parameters are presented in the tables which follow:

TABLE D-1 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR THE STATIC STRENGTH OF SIMPLE SPECIMENS

Specimen No.	I	Fs_I (lb/in.)	C (8, 8, I)	A (8, 8, I)	$\ell n\ Fs_I$	C (8, 8, I) $\ell n\ Fs_I$	A (8, 8, I) $\ell n\ Fs_I$
73	1	5270	–0.093270	0.034052	8.56979	–0.799304	0.29182
83	2	5316	–0.098886	0.053552	8.57848	–0.848291	0.45939
84	3	5465	–0.093994	0.073452	8.60612	–0.808924	0.63214
7	4	6008	–0.079752	0.095062	8.70085	–0.693910	0.82712
20	5	6427	–0.053918	0.119768	8.76826	–0.472767	1.05016
46	6	6446	–0.010179	0.149934	8.77122	–0.089282	1.31510
25	7	6463	0.069325	0.191236	8.77385	0.608247	1.67788
58	8	6501	0.360675	0.282943	8.77971	3.166622	2.48416
		Avg 5987				Σ = 0.062391	Σ = 8.73777

GP74-1037-207

E (LB) = 0.08501680; E (CP) = –0.02386561

α_s = 14.6653 β_s = 6223.8253

TABLE D-2 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR LIFETIME OF SIMPLE SPECIMENS

Specimen No.	I	T_I (Lifetimes)	C (7, 7, I)	A (7, 7, I)	$\ell n\ T_I$	C (7, 7, I) $\ell n\ T_I$	A (7, 7, I) $\ell n\ T_I$
6	1	1.6850	−0.108323	0.038743	0.52177	−0.05652	0.02021
88	2	2.1700	−0.113479	0.064086	0.77473	−0.08792	0.04965
66	3	3.0200	−0.103569	0.090785	1.10526	−0.11447	0.10034
21	4	4.4250	−0.078748	0.120971	1.48727	−0.11712	0.17992
23	5	4.5000	−0.032632	0.157657	1.50408	−0.04908	0.23713
24	6	4.5625	0.054727	0.207825	1.51787	0.08307	0.31545
32	7	4.7700	0.382022	0.319934	1.56235	0.59685	0.49985
	Avg 3.5904					ϵ = 0.25481	ϵ = 1.40255

E (lb) = 0.09836496 E (CP) = −0.02578937

α_f = 3.53845 β_f = 4.0360

TABLE D-3 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR THE STATIC STRENGTH OF SMALL SCALE STEP-LAP SPECIMENS

Specimen No.	I	F_{S_I} (lb/in.)	C (10, 10, I)	A (10, 10, I)	$\ell n\ F_{S_I}$	C (10, 10, I) $\ell n\ F_{S_I}$	A (10, 10, I) $\ell n\ F_{S_I}$
1	1	15,392	−0.072734	0.027331	9.64160	−0.70127	0.26351
3	2	16,239	−0.077971	0.040034	9.69517	−0.75594	0.38814
69	3	16,955	−0.077242	0.052496	9.73832	−0.75221	0.51122
68	4	17,023	−0.071876	0.065408	9.74232	−0.70024	0.63723
67	5	17,261	−0.061652	0.079263	9.75620	−0.60149	0.77331
2	6	17,581	−0.045420	0.094638	9.77457	−0.44396	0.92505
70	7	17,683	−0.020698	0.112414	9.78036	−0.20243	1.09945
36A	8	18,256	0.017927	0.134239	9.81225	+0.17590	1.31719
66	9	18,484	0.085070	0.164178	9.82466	+0.83578	1.61299
65	10	18,638	0.324597	0.230001	9.83296	+3.19175	2.26159
		Avg = 17,351				Σ = 0.04589	Σ = 9.78968

GP74-1037-202

E (LB) = 0.06679250; E (CP) = −0.02050852

α_s = 20.33760 β_s = 17,830.57572

TABLE D-4 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR LIFETIME OF SMALL SCALE STEP-LAP SPECIMENS

Subgroup I

1 Specimen (19) Went 6.0 Lifetimes With No Failures

E (lb) = 0.15690540 E (CP) = 0.00888019 $\alpha_{f_I} = 2.47115$ $\beta_{f_I} = 4.32114$ $\gamma_I = 0.18611$

Specimen No.	I	T_I	C (6, 5, I)	A (6, 5, I)	ℓn T_I	C (6, 5, I) ℓn T_I	A (6, 5, I) ℓn T_I
26	1	2.0000	−0.16992	0.007521	0.69315	−0.11778	0.00521
9	2	2.0000	−0.166319	0.048328	0.69315	−0.11528	0.03350
7	3	3.5000	−0.129510	0.101608	1.25276	−0.16225	0.12729
27	4	4.1510	−0.054453	0.172859	1.42335	−0.07751	0.24604
31	5	4.7815	0.520201	0.669685	1.56475	0.81399	1.04789
						Σ= 0.34117	Σ= 1.45993

GP75-0332-72

Subgroup II

1 Specimen (30 Went 6.0 Lifetimes With No Failures

E (lb) = 0.12760617 E (CP) = 0.00130057 $\alpha_{f_{II}} = 2.30340$ $\beta_{f_{II}} = 4.10855$ $\gamma_{II} = 0.14627$

Specimen No.	I	T_I	C (7, 6, I)	A (7, 6, I)	ℓn T_I	C (7, 6, I) ℓn T_I	A (7, 6, I) ℓn T_I
28	1	1.8118	−0.138436	0.013524	0.59432	−0.08228	0.00804
32	2	1.9013	−0.140342	0.041588	0.64254	−0.09018	0.02672
23	3	2.4050	−0.121821	0.075499	0.87755	−0.10690	0.06625
25	4	3.4057	−0.082938	0.117461	1.22545	−0.10164	0.14394
17	5	4.5000	−0.015394	0.172092	1.50408	−0.02315	0.25884
40	6	4.8025	0.498931	0.579835	1.56914	0.78289	0.90984
						Σ= 0.37874	Σ= 1.41363

GP75-0332-73

TABLE D-4 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR LIFETIME OF SMALL SCALE STEP-LAP SPECIMENS (Continued)

Subgroup III

E (lb) = 0.08501680 E (CP) = −0.02386561 $\alpha_{f_{III}}$ = 2.40593 $\beta_{f_{III}}$ = 3.93645 γ_{III} = 0.09292

Specimen No.	I	T_I	C (8, 8, I)	A (8, 8, I)	$\ell n\ T_I$	C (8, 8, I) $\ell n\ T_I$	A (8, 8, I) $\ell n\ T_I$
43	1	1.7698	−0.093270	0.034052	0.57087	−0.05324	0.01944
8	2	2.0000	−0.098886	0.053552	0.69315	−0.06854	0.03712
24	3	2.0000	−0.093994	0.073452	0.69315	−0.06515	0.05091
35	4	2.5000	−0.079752	0.095062	0.91629	−0.07308	0.08710
22	5	3.8913	−0.053918	0.119768	1.35874	−0.07326	0.16273
34	6	4.5000	−0.010179	0.149934	1.50408	−0.01531	0.22551
18	7	5.1798	0.069325	0.191236	1.64477	0.11402	0.31454
15	8	5.5000	0.360675	0.282943	1.70475	0.61486	0.48235
						Σ= 0.38030	Σ= 1.38020

GP75-0332-74

Subgroup IV

E (lb) = 0.09836496 E (CP) = −0.02578937 $\alpha_{f_{IV}}$ = 2.67860, $\beta_{f_{IV}}$ = 4.08920 γ_{IV} = 0.10910

Specimen No.	I	T_I	C (7, 7, I)	A (7, 7, I)	$\ell n\ T_I$	C (7, 7, I) $\ell n\ T_I$	A (7, 7, I) $\ell n\ T_I$
38	1	1.9018	−0.108323	0.038743	0.64280	−0.06963	0.02490
29	2	2.0000	−0.113479	0.064086	0.69315	−0.07866	0.04442
37	3	2.6483	−0.103569	0.090785	0.97392	−0.10087	0.08842
41	4	3.5000	−0.078748	0.120971	1.25276	−0.09865	0.15155
42	5	4.3935	−0.032632	0.157657	1.48013	−0.04830	0.23335
14	6	5.0303	0.054727	0.207825	1.61548	0.08841	0.33574
20	7	5.4010	0.382022	0.319934	1.68658	0.64431	0.53960
						Σ= 0.33661	Σ= 1.41798

GP75-0332-75

TABLE D-4 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR LIFETIME OF SMALL SCALE STEP-LAP SPECIMENS (Concluded)

Subgroup V

E (lb) = 0.08501680 E (CP) = 0.02386561 α_{f_V} = 2.93100 β_{f_V} = 4.01072

γ_V = 0.09292

Specimen No.	I	T_I	C (8, 8, I)	A (8, 8, I)	$\ell n\ T_I$	C (8, 8, I) $\ell n\ T_I$	A (8, 8, I) $\ell n\ T_I$
33	1	2.0000	−0.093270	0.034052	0.69315	−0.06465	0.02360
10	2	2.0000	−0.098886	0.053552	0.69315	−0.06854	0.03712
64	3	2.2505	−0.093994	0.073452	0.81115	−0.07624	0.05958
21	4	3.5000	−0.079752	0.095062	1.25276	−0.09991	0.11909
13	5	4.0550	−0.053918	0.119768	1.39995	−0.07548	0.16767
39	6	4.1050	−0.010179	0.149934	1.41221	−0.01437	0.21174
6	7	5.0000	0.069325	0.191236	1.60944	0.11157	0.30778
18	8	5.2750	0.360675	0.282943	1.66298	0.59979	0.47053
						Σ =0.31217	Σ = 1.39711

THE PARAMETERS FOR THE GROUP ARE

α_f = 2.52659 β_f = 4.12828

TABLE D-5 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR THE STATIC STRENGTH OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE, BASELINE SPECTRUM

Specimen No.	I	Fs_I (lb/in.)	C (10, 10, I)	A (10, 10, I)	$\ell n\, Fs_I$	C (10, 10, I) $\ell n Fs_I$	A (10, 10, I) $\ell n Fs_I$
83	1	16,523	−0.072734	0.027331	9.71251	−0.70643	0.26545
49	2	18,868	−0.077971	0.040034	9.84522	−0.76764	0.39414
86	3	19,204	−0.077242	0.052496	9.86287	−0.76183	0.51776
82	4	20,137	−0.071876	0.065408	9.91031	−0.71231	0.64821
85	5	20,391	−0.061652	0.079263	9.92285	−0.61176	0.78651
84	6	20,763	−0.045420	0.094638	9.94093	−0.45152	0.94079
81	7	20,815	−0.020698	0.112414	9.94343	−0.20581	1.11778
2	8	21,254	0.017927	0.134239	9.96430	0.17863	1.33760
3	9	21,255	0.085070	0.164178	9.96435	0.84767	1.63593
1	10	21,821	0.324597	0.230001	9.99063	3.24293	2.29785
		Avg = 20,103				Σ = 0.05193	Σ = 9.94202

GP74-1037-225

E (LB) = 0.06679250; E (CP) = −0.02050852

α_s = 17.96945 β_s = 20,762

TABLE D-6 CALCULATION FOR THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR THE STATIC STRENGTH OF FULL SCALE STEP-LAP SPECIMENS AT 350°F

Specimen No.	I	Fs_I (lb/in.)	C (6, 6, I)	A (6, 6, I)	$\ell n Fs_I$	C (6, 6, I) $\ell n Fs_I$	A (6, 6, I) $\ell n Fs_I$
61	1	15,728	−0.128810	0.044826	9.66320	−1.24472	0.43316
64	2	15,788	−0.132102	0.079377	9.66701	−1.27703	0.76734
63	3	16,138	−0.111951	0.117541	9.68893	−1.08469	1.13885
66	4	16,179	−0.064666	0.163591	9.69147	−0.62671	1.58544
62	5	16,244	0.031796	0.226486	9.69548	0.30828	2.19589
65	6	16,483	0.405733	0.368179	9.71008	3.93970	3.57505
		Avg = 16,093				Σ = 0.01483	Σ = 9.69573

GP74-1037-226

E (LB) = 0.11657671; E (CP) = −0.02771574

α_s = 59.55926 β_s = 16,240

TABLE D-7 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR LIFETIME OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE, BASELINE SPECTRUM

Subgroup I

7 Specimens (14, 16, 24, 28, 30, 33, 35) went 6.0 Lifetimes with no Failures

Specimen No.	I	T_I (Lifetimes)	C (14, 7, I)	A (14, 7, I)	ℓnT_I	C (14, 7, I) ℓnT_I	A (14, 7, I) ℓnT_I
87	1	1.5000	−0.130915	−0.078656	0.40547	−0.05308	−0.03189
50	2	2.0000	−0.132521	−0.068666	0.69315	−0.09186	−0.04760
89	3	2.0000	−0.126123	−0.052554	0.69315	−0.08742	−0.03643
6	4	3.0325	−0.114051	−0.031776	1.10939	−0.12653	−0.03525
17	5	3.5000	−0.096788	−0.006522	1.25276	−0.12125	−0.00817
27	6	5.1510	−0.074184	0.023467	1.63919	−0.12160	0.03847
8	7	5.5927	0.674581	1.214708	1.72146	1.16127	2.09107
		Avg = 3.2537				Σ = 0.55953	Σ = 1.97020

GP74-1037-211

E (LB) = 0.12547311; E (CP) = 0.08030259

α_f = 1.56296 β_f = 7.5502

Subgroup II

6 Specimens (15, 18, 25, 29, 32, 34) went 6.0 Lifetimes with no Failures

Specimen No.	I	T_I (Lifetimes)	C (14, 8, I)	A (14, 8, I)	ℓnT_I	C (14, 8, I) ℓnT_I	A (14, 8, I) ℓnT_I
79	1	2.0000	−0.112041	−0.048365	0.69315	−0.07766	−0.03352
88	2	2.5000	−0.114637	−0.039964	0.91629	−0.10504	−0.03662
48	3	3.1123	−0.110509	−0.027495	1.13536	−0.12547	−0.03122
7	4	4.1250	−0.101635	−0.011849	1.41707	−0.14402	−0.01679
9	5	4.5000	−0.088422	0.006905	1.50408	−0.13299	0.01039
31	6	5.4010	−0.070735	0.029002	1.68658	−0.11930	0.04891
19	7	5.5000	−0.048074	0.054897	1.70475	−0.08195	0.09359
26	8	5.6070	0.646052	1.036868	1.72402	1.11380	1.78758
		Avg = 4.0932				Σ = 0.32737	Σ = 1.82232

GP74-1037-212

E (LB) = 0.10683049; E (CP) = 0.05038249

α_f = 2.72829 β_f = 6.30149

GROUP ESTIMATES ARE

α_F = 2.19849 β_F = 6.8692

TABLE D-8 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR LIFETIME , OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE WITH LOADING FREQUENCY SLOWED TO 1/8 OF BASELINE

Two Specimens (22 and 23) Went 6.0 Lifetimes with no Failure

Specimen No.	I	T_I (Lifetimes)	C (6, 4, I)	A (6, 4, I)	ℓnT_I	C (6, 4, I) ℓnT_I	A (6, 4, I) ℓnT_I
20	1	2.0000	−0.225141	−0.063569	0.69315	−0.15606	−0.04406
21	2	3.2580	−0.209083	−0.006726	1.18111	−0.24695	−0.00794
13	3	4.1258	−0.146386	0.079882	1.41726	−0.20747	0.11321
12	4	5.1820	0.580610	0.990412	1.64519	0.95521	1.62942
						Σ = 0.34473	Σ = 1.69063

E (LB) = 0.21242254 E (CP) = 0.0803562

GP74-1037-210

α_f = 2.28462 β_f = 5.61701

TABLE D-9 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR LIFETIME, OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE WITH ADDITIONAL LOW LOAD LEVELS INCLUDED

Specimen No.	I	T_I (Lifetimes)	C (3, 3, I)	A (3, 3, I)	ℓnT_I	C (3, 3, I) ℓnT_I	A (3, 3, I) ℓnT_I
10	1	1.4060	−0.278666	0.081063	0.34075	−0.09496	0.02762
80	2	1.6543	−0.190239	0.251001	0.50338	−0.09576	0.12635
11	3	2.0000	0.468904	0.667936	0.69315	0.32502	0.46298
		Avg = 1.6867				Σ = 0.13430	Σ = 0.61695

GP74-1037-213

E (LB) = 0.25634620; E (CP) = −0.01842169

α_f = 5.55864 β_f = 1.8471

TABLE D-10 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR LIFETIME OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE WITH 10 TIMES BASELINE RELAXATION

Specimen No.	I	T_I (Lifetimes)	C (6, 6, I)	A (6, 6, I)	$\ell n T_I$	C (6, 6, I) $\ell n T_I$	A (6, 6, I) $\ell n T_I$
56	1	0.5000	−0.128810	0.044826	−0.69315	+0.08928	−0.03107
57	2	1.5000	−0.132102	0.079377	0.40547	−0.05356	0.03218
74	3	2.0000	−0.111951	0.117541	0.69315	−0.07760	0.08147
71	4	3.1108	−0.064666	0.163591	1.13488	−0.07339	0.18566
73	5	3.5000	0.031796	0.226486	1.25276	0.03983	0.28373
72	6	4.5000	0.405733	0.368179	1.50408	0.61025	0.55377
		Avg = 2.5185				Σ = 0.53481	Σ = 1.10574

GP74-1037-214

E (LB) = 0.11657671; E (CP) = −0.02771574

α_f = 1.65186 β_f = 2.97119

TABLE D-11 CALCULATION OF THE BLU ESTIMATES OF THE WEIBULL PARAMETERS FOR LIFETIME, OF FULL SCALE STEP-LAP SPECIMENS AT ROOM TEMPERATURE WITH HIGH LOADS EXCLUDED

Specimen No.	I	T_I (Lifetimes)	C (6, 6, I)	A (6, 6, I)	$\ell n T_I$	C (6, 6, I) $\ell n T_I$	A (6, 6, I) $\ell n T_I$
90	1	1.1645	−0.278666	0.081063	0.15229	−0.04244	0.01235
78	2	4.1510	−0.190239	0.251001	1.42335	−0.27078	0.35726
77	3	4.1510	0.468904	0.667936	1.42335	0.71011	0.95071
		Avg = 3.1556				Σ = 0.39689	Σ = 1.32032

GP74-1037-215

E (LB) = 0.25634620; E (CP) = −0.01842169

α_f = 1.87371 β_f = 3.7080

APPENDIX E

GRAPHICAL DETERMINATION OF WEIBULL PARAMETERS

If the strength, F, of a particular type of specimen has a Weibull distribution equation (F-1) holds

$$P_S\ (F > f) = \exp - (f/\beta)^{\alpha} \qquad \text{(F-1)}$$

where P_S is the probability that a given specimen will have a strength greater f and α and β are the shape and scale parameter respectively.

Equation (F-1) can alternately be written as equation (F-2).

$$\ln \ln \frac{1}{P_S} = \alpha(\ln f - \ln \beta) \qquad \text{(F-2)}$$

In this form it is seen that a plot of $\ln \ln \frac{1}{P_S}$ vs ln f is linear. The slope of that line is α and at the point where $\ln \ln \frac{1}{P_S} = 0$ (ie $P_S = 1/e$) $\ln f = \ln \beta$.

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